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THESIS

COMPUTER AIDED DATA ACQUISITION AND CONTROL
OF AN INTERNAL COMBUSTION ENGINE

by

Bryan R. Oakes

March 1984

Thesis Advisor: W.G. Culbreth

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Computer Aided Data Acquisition and Control of an Internal Combustion Engine

by

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Submitted in partial fulfillment of the requirements for the degree of

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from the

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March 1984

ABSTRACT

Two microcomputers, a Digital Equipment Corporation VT-103 and an Octagon Systems Corporation SYS-1, were interfaced with a General Motors Model 1-53X3 single cylinder diesel engine to provide automated data acquisition and data reduction and engine control while running classroom experiments. Engine inlet and exhaust temperatures and pressures, RPM, torque and fuel flow along with additional engine parameters can be measured with the aid of a computer. Values for parameters such as specific fuel consumption, air-to-fuel ratio, and thermal efficiency can then be computed and both measured and computed values can be displayed and recorded. The Digital Equipment Corporation computer is the parent computer and is used interactively for data acquisition and data reduction and for feedback control through the Octagon computer to which it is linked. The Octagon computer is used exclusively for control of the engine speed and load.

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NOMENCLATURE

TEXT

A --- proportional gain constant
A/D - analog-to-digital
B --- integral gain constant
C --- differential gain constant
D/A - digital-to-analog
e_n -- error at time n
E(t)- error as a function of time
E(s)- Laplace transform of error function
I --- voltage to field current controller
K --- steady-state gain
PIO - Peripheral interface chip (input/output)
t --- time constant
t_s -- settling time
T --- torque
T_s -- sampling time
V --- voltage to diesel engine throttle servo
$\dot{X}$ --- throttle position
$\dot{\theta}$ --- engine speed (radians/sec)
δ --- damping ratio
ω --- frequency
subscripts
1 - diesel engine
2 - throttle
3 - dynamometer

CONTROL PROGRAM

A --- integration of function Y
D --- differentiation of function E
E --- error between requested and measured RPM
F --- function E from previous iteration
G --- differentiation of function Y
I --- integration of function E
J --- change in load control output
L --- load control output
M --- measured RPM
N --- RPM control output
R --- requested RPM
T --- requested torque
V --- change in speed control output
X --- measured torque
Y --- error between requested and measured torque
Z --- function Y from previous iteration

DATA ACQUISITION PROGRAM

```
AF --- air-to-fuel ratio (lbm air/lbm fuel)
API -- American Petroleum Institute standard (60 deg F)
AREA - area of air inlet nozzle (in^2)
AVE(I) average value from I'th channel
BHP -- brake horsepower (Hp)
DN --- diameter of air inlet nozzle (in)
FHP -- friction horsepower (Hp)
FST -- temperature of fuel sample (deg F)
FTORQ- friction torque (lbf-ft)
IHP -- indicated horsepower (Hp)
IOUT - RPM and torque output to control computer
IR --- requested RPM converted to a numerical range of 0-255
IRPM - requested RPM
IRUN - counter for printed output
IT --- requested torque
L ---- requested torque converted to a numerical range of 0-255
LHV -- lower heating value of fuel
MAIR - air mass flow rate (lbm/sec)
MECH - mechanical efficiency of engine
MEP -- mean effective pressure (psia)
MF --- measured fuel mass flow rate (no specific gravity
       correction), (lbm/sec)
MFUEL- fuel mass flow rate (lbm/sec)
MWTR - coolant mass flow rate (lbm/sec)
OCT -- octal A/D channel select
PA --- atmospheric pressure (psia)
PAIR - inlet air pressure (psia)
PATM - atmospheric pressure (in Hg)
PEXH - exhaust gas pressure (psia)
PIN -- blower air pressure (psia)
P1 --- differential air inlet pressure (in H20)
P2 --- differential blower air pressure (in Hg)
P3 --- differential exhaust gas pressure (in H20)
RPM -- measured engine RPM
SCAV - air scavenge ratio
SD(I)- standard deviation from channel I
SFC -- specific fuel consumption (lbm/Hp-hr)
SG60 - specific gravity of fuel at 60 deg F
SGFUEL specific gravity of fuel entering engine
SPGR - specific gravity of fuel sample
S1 --- measured RPM
TAIR - inlet air temperature (deg F)
TEXH - exhaust gas temperature (deg F)
TFUEL- fuel temperature (deg F)
THERM- engine thermal efficiency
TORQ - measured torque (lbf-ft)
TWIN - water temperature entering cooler (deg F)
TWOUT- water temperature leaving cooler (deg F)
T1 --- measure torque (lbf-ft)
```

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I. INTRODUCTION

A computer aided data acquisition, data reduction and engine control system was constructed and tested on a diesel engine test stand used for laboratory experimentation. The engine used was a General Motors model 1-54X3 diesel engine. The engine was coupled to a DC motor generator which was used as a dynamometer to place a variable load on the engine. Power generated was dissipated in a resistor load bank.

In the past, whenever the unit was used for classroom experimentation, the recording of engine parameters and the reduction of the data was done by hand. A technician was also required to run the engine during testing. In order to more efficiently and accurately record data and to allow a means of immediately reducing and displaying the engine's performance parameters, a microprocessor-based data acquisition and data reduction system was designed. In addition, in order to reduce the need for a technician and to allow the engine to be brought to a desired operating point for study more quickly and easily, a microprocessor-based control system was designed for both the engine and dynamometer.

An Octagon SYS-1 8-bit microcomputer was chosen as the control computer. Digital-to-analog and analog-to-digital

converters were built to allow the computer to interface with transducers attached to the engine/dynamometer unit. The transfer functions for both the diesel engine and the dynamometer were experimentally determined and used to design an acceptable control algorithm for use by the control computer.

The use of the microcomputer in the feedback control loops allowed the use of almost any control action. A proportional-plus-integral-plus-differential (PID) control action was chosen [Ref. 1] [Ref. 2]. The use of a PID control action allows the designer of a control system a measure of control over the speed of response of the system to a step input and gives acceptable steady state accuracy when used with the hardware available. The values for the three constants associated with each PID controller; engine and dynamometer; were initially determined using Bodie diagrams of the open loop frequency response curves. A short control program was written for the control computer using the analytically determined values for the constants and the program was tested after being installed in the system. The final values for the constants used in the control program were experimentally determined.

For data acquisition and data reduction, a Digital Equipment Corporation VT-103 desktop computer was used. The VT-103 was interfaced with the SYS-1 computer to allow user

input of desired engine RPM and load. The Digital computer included a 16 channel analog-to-digital converter that provided a means of linking the computer to the sensing devices installed on the diesel engine test stand. An interactive FORTRAN program was written that allowed the user to run a variety of experiments on the system while controlling the engine RPM and load.

II. HISTORY

The use of microprocessors in control and data acquisition applications has grown dramatically since the early 1970's. Computers were first used for control in the preceeding decade. Early in the 60's, after computers began to be used in business applications, the advantages of computers as a process control device first began to become apparent.

Computers had several advantages over conventional control devices. Until the advent of computers, process control was generally broken down into as many simple control systems as possible. The only device capable of reading a large number of parameters and making control decisions based on all of them was a human. Computers, both analog and digital, because they could perform complex computations with constant accuracy and at high speed, became desirable as integral parts of complex manufacturing and industrial process control systems. In most cases, even though they were expensive, they were more cost efficient and accurate than the human operators they replaced.

During this same time period the advantages of digital over analog computers became apparent. Almost any desired increase of accuracy could be achieved using digital

computers with relatively little increase in cost due to the increased accuracy. It was almost impossible to increase the accuracy of analog computers without greatly increasing the cost of the computer.

Early in the 1970's the first microcomputer chips became available on the market. INTEL marketed the first 8-bit microprocessor in 1972. The first applications of the new microprocessors were in hand held calculators, but inexpensive microcomputers (8-bit) and minicomputers (16-bit) based on the new chips soon followed.

Since the early 70's, the applications of microprocessors has grown rapidly. The cost of the computers dropped exponentially during the decade and at the same time reliability improved. Microcomputers are now used in such diverse control areas as chemical process control, aircraft control and machining. In all of these applications the microprocessor samples parameters and makes control decisions based on the samples.

The first applications of computer process control required new methods of analysis of the control problem. Digital computers were unable to sample control parameters continuously, instead, the computer would sample once during a discrete time period. This led to the development of new methods for analyzing the control problem. Continuous methods of analysis can still be used in some cases but they

may not be as accurate as some of the discrete time period methods [Ref. 3].

One of the first applications of computers was in data reduction. When first employed in this capacity, data that had been recorded by hand was entered into a computer which would then perform the necessary calculations. The technology that made computer process control possible also made computer-aided data acquisition possible. The interfaces between the analog real world and the digital computers necessary for the measurement of control parameters, also allowed computers to record data in addition to reducing data.

III. DESCRIPTION OF SYSTEM HARDWARE

The design of both the data acquisition/data reduction subsystem and the control subsystem evolved around existing hardware. An effort was also made to use existing hardware when available and to limit the cost of any item that needed to be purchased or manufactured. The diesel engine and dynamometer have been in use since 1960. The system was upgraded in 1979 to include more up-to-date transducers and measurement devices and digital readouts of many of the student recorded parameters and a new control console for use by the technician running the engine. At the time of the update, provisions were made to install a control system and a data acquisition system when it became available. The layout of the engine and dynamometer and associated equipment is shown in Figure 1.

A. ENGINE AND ASSOCIATED HARDWARE

The engine used in the experiment was a General Motors Model 1-53X3 two stroke-cycle diesel engine. The engine was coupled to a DC motor generator that could be used as a dynamometer by feeding the generated current to a load bank to be dissipated as heat or that could be used as an electric motor to start the diesel.

A total of eleven parameters associated with the diesel engine needed to be measurable by the data acquisition

computer. This required that the output from all transducers be converted to a voltage range that was compatible with transistor-transistor logic (TTL) devices. Many of the existing transducers had signals already conditioned to be used by the computer.

Six Newport pyrometers were installed to measure intake and exhaust gas temperatures, coolant temperatures, fuel temperature and ambient air temperature. The pyrometers had a signal output that varied between 0 and +5 volts DC and required no additional electronics to be used with the data acquisition computer.

Pressures had in the past been measured using mercury and water manometers. Three strain gage differential pressure transducers were purchased which included the electronic circuitry necessary to amplify the strain gage output to the range of 0 to +5 volts.

Another differential pressure transducer was purchased to measure torque. The existing torque measuring device consisted of a bellows attached to a lever arm linked to the dynamometer. A pressure sensing Bourdon tube analog meter converted the pressure from the bellows to a torque reading. The differential pressure transducer was installed in series with the existing gage and calibrated to measure lbf-ft. Engine RPM was measured with a magnetic pickup on the dynamometer shaft. Fuel flow was measured with a turbine flow

meter. Both of these transducers produce variable frequency signals. Instrumentation amplifiers were used to convert the frequency output to a variable voltage for use by the computer. Provisions were also made to measure coolant mass flow but a transducer was yet to be installed. A list of all of the sensors and their characteristics is found in Appendix A.

B. DATA ACQUISITION AND DATA REDUCTION SYSTEM HARDWARE

A Digital Equipment Corporation VT-103 microcomputer was available to be used for data acquisition/reduction, or engine control, or both. The VT-103 was a 16-bit microcomputer based on DEC's LSI-11 microprocessor. The computer came with an 8 slot bus that could be configured with a number of hardware options dependent on the needs of the user. It could be programmed in FORTRAN and had an operating system with a number of subroutines callable from FORTRAN programs that made it very easy to access various hardware options without the need of software drivers; analog-to-digital converters, digital-to-analog converters, serial interfaces and parallel interfaces.

The decision was made to dedicate the VT-103 to data acquisition and data reduction. An interface was eventually provided to connect the control computer with the VT-103.

To properly run a variety of experiments and to allow the user a certain amount of flexibility, it was anticipated that an interactive data acquisition/reduction program would

be needed. The flexibility and ease of programming made the VT-103 ideal for this application. It was originally felt that the control computer would also need an interactive program to allow the user a means of changing the operating parameters of the engine. Instead, the two computers were interfaced through an asynchronous parallel line. This greatly simplified the programming required by the control computer and allowed all of the control functions in addition to all of the data acquisition functions to be performed by the operator on one terminal.

In the final configuration the VT-103 computer required a means of storing the final program, a terminal for interactive display, a printer, a multi-channel analog-to-digital converter, and a parallel port for interfacing with the control computer. Figure 2 show the configuration of the VT-103 backplane with all of the required options.

The LSI-11 microprocessor with 4K by 16-bit random access memory (RAM) resided in slots 1 and 2 of the backplane. Slot 3 held a multifunction module. This module contained an additional 4K by 16-bit read/write memory and two asynchronous line interfaces. The interfaces were used to connect the microprocessor to the terminal and to the internal tape drives. Slot 4 contained an additional 32K by 16-bit RAM. The serial port for the printer resided in slot 5; and the parallel port for the control computer resided in slot 6. Slots 7 and 8 were for the 16 channel by 12-bit

analog-to-digital (A/D) converter. Complete descriptions of the boards and their applications can be found in Digital's microcomputer handbooks [Ref. 4] and [Ref. 5].

C. CONTROL SYSTEM HARDWARE

The hardware required for the control system did not need to be nearly as complex as the hardware required for data acquisition/reduction. For the engine and dynamometer control, only two parameters needed to be measured; engine RPM and torque; and two control voltages needed to be outputted; one to the diesel engine throttle servo and one to the dynamometer field current controller. Both the servo and field current controller were already configured to be actuated by voltages in the range of TTL devices. Although a terminal was not required in the final configuration, one was installed while programming the control computer and while making dynamic adjustments to the program.

An Octagon SYS-1 microcomputer was available for use as the control computer. The SYS-1 was based on the INS8073 microcomputer chip. It was an 8-bit computer that came with an RS232 input/output port and a three channel peripheral interface chip (PIO). In addition, all of the INS8073 pins were available at a 44 pin edge connector that functioned as a bus. All of the circuitry for the SYS-1 was located on one 5x7 circuit board. A schematic of the computer can be found in the SYS-1 User's Guide [Ref. 6] or in an article by McKown and Sarns [Ref. 7]. In addition to the microprocessor

the board contained 4K of RAM, a utility program held in a 1K byte eraseable programmable memory (EPROM) chip and another EPROM that could be programmed by the user.

The SYS-1 did not come with an A/D converter or a digital-to-analog (D/A) converter. Both were needed in the final system. The A/D converter was necessary to read the output from the RPM and torque measuring transducers and the D/A converters to convert the digital control signals to control voltages. Rather than purchase the necessary hardware it was felt that they could as easily be built. Figure 3 is the schematic for the D/A converter that was designed to be used with the SYS-1. Figure 4 is the schematic of the A/D converter. Each was built on a separate circuit board and, except for the voltage inputs to the A/D board and the voltage outputs from the D/A board, used the same layout for the 44-pin edge connectors as the SYS-1.

The A/D converter was an 8 channel by 8-bit converter. Only two channels are presently used. The D/A converter had three channels and was also an 8-bit converter. Only two of its channels were used.

The three channel PID was used to interface the SYS-1 with the data acquisition computer. Two of the 8-bit channels were connected to the 16-bit parallel port of the VT-103. The 8 high bits from the VT-103 parallel port were connected to channel B of the SYS-1 and the 8 low bits were connected to channel A.

IV. DATA ACQUISITION AND DATA REDUCTION THEORY

The data acquisition system was based on the Digital VT-103 minicomputer which used a 12-bit, 16-channel analog-to-digital (A/D) converter to sample various parameters associated with engine performance. Prior to designing the software associated with the system, decisions were required on sampling rate and the number of samples and an analysis needed to be made to determine the accuracy of the data acquisition system.

A. ANALOG-TO-DIGITAL CONVERSION

A computer's central processing unit performs all of its functions using binary numbers. In general, a computer cannot sense or use any analog signal directly. The analog-to-digital converter acts as the interface between an analog device such as a transducer and the central processing unit of a computer. The analog-to-digital converter does this by converting an analog signal to a binary number that corresponds to the magnitude or strength of the signal. An 8-bit analog-to-digital converter will convert an analog voltage to a binary number between 00000000 and 11111111 (0 and 255 decimal). A 12-bit analog converter can convert an analog voltage into an integer number between 0 and 4095 decimal.

The VT-103 used a 16 channel 12-bit analog-to-digital converter. Only 10 of the channels were required to measure the diesel engine parameters. All of the parameters were converted to voltages between 0 and +5 volts DC by the transducers and their associated signal conditioning devices. The A/D converter used in this system could accept signals in the range of -5 to +5 volts. A signal of -5 volts would be converted to decimal 0 while a signal of +5 volts will be converted to decimal 4095. It should be noted that if the signal had a potential of 0 volts the computer will read 2048, not 0.

The A/D converter used with the VT-103 was a successive approximation analog-to-digital converter. It converted an analog signal by successively comparing the signal to various reference voltages through a series of resistors. The 12-bit converter used with the VT-103 required twelve successive comparisons to convert one signal to a binary number.

The resolution of the 12-bit converter was equal to 1/4095 times the acceptable input range of the analog signal. Since the VT-103 A/D converter could accept signals between -5 and +5 volts, the resolution of the converter used in this system is equal to,

$$(1/4095) \times 10 \text{ volts} = \pm 0.00244 \text{ volts} \qquad \text{(eqn. 4.1)}$$

To calculate the resolution of the converter in engineering units, the resolution of the converter is divided by the resolution of the transducer given in volts/unit. As an example, the resolution of the Newport pyrometers was .001 volts/degree F. This gives a temperature resolution of the A/D converter of,

$$.00244/.001 = \pm 2.44 \text{ degrees F} \qquad \text{(eqn. 4.2)}$$

A more practical method of computing the resolution of the A/D converter is through the use of the data that was collected for the converter calibration. The range measured in engineering units can be divided by the range of A/D converter values to give the same result. Using the same temperature example, temperatures were measured between 60 and 638 degrees F, a range of 578 degrees F. The A/D converter values ranged from 2068 to 2297, a range of 229. Dividing the temperature range by the A/D range gives a resolution of ± 2.52 degrees F. The resolution of every channel used in this system is given in Appendix B along with the data used to calibrate the analog-to-digital converter.

B. NYQUIST CRITERION AND NUMBER OF SAMPLES

Two additional factors are normally considered when designing a computer-aided data acquisition system; the

frequency that data is sampled and the number of representative samples to be taken and averaged for any set of calculations.

The Nyquist criterion gives a good indication of the frequency that data should be sampled. According to the criterion, samples should be taken at a frequency at least twice that of the highest natural frequency of interest. A good explanation of the need for Nyquist criterion can be found in Pearson's article on processing analog signals which appeared in Popular Electronics [Ref. 8]. Sampling at twice the highest frequency prevents signal aliasing; interpreting the signal as a lower frequency signal than it really is. Since all data for the diesel is taken while the diesel is running at a constant RPM and load, i.e., steady state, there is no danger of sampling the data too slowly. In actuality, the computer samples data so quickly that problems associated with low frequency sampling do not occur.

The second factor considered is the number of samples needed to be taken in order to calculate the value of any parameter with reasonable accuracy. No criterion was used to determine the number of samples. Instead, the program was written to take an arbitrary number of samples (100) and compute the average value and the standard deviation of the 100 samples for each channel. For most channels, the

standard deviation was consistently less than 1/4095 or 0.02% For engine RPM the standard deviation varied slightly around 13 out of 4096 or 0.24%. This accuracy corresponded to ±12 RPM.

C. CALIBRATION OF THE DIGITAL-TO-ANALOG CONVERTER

For each data run, after the computer sampled and averaged the data, the decimal numbers representing the amplitude of the various parameters needed to be converted to engineering units. This was done to make it easier to program the calculations necessary to compute the performance parameters of the engine and to put the data in a form that could be easily understood by the user.

To calibrate the digital-to-analog converter, data was collected for a number of points within the range that was expected to be measured by each A/D converter channel. A linear curve was then fit to the data and the curve fit coefficients entered as part of the data acquisition program. The raw data used to calibrate each A/D converter channel is included in Appendix B. Plots of both the data and the linear curve fit equations are included in Appendix C.

V. DATA ACQUISITION PROGRAM

The data acquisition and data reduction program, listed in Appendix D, was written entirely in FORTRAN IV. The program was written on a Digital VT-103 computer, similar to the system used with the diesel engine, which was equipped with an 8 inch dual disk drive. The dual disk drive allowed the use of the FORTRAN compiler. After the program was written and compiled, the compiled code was stored on a tape cassette using one of the two internal tape drives of the VT-103. The tape was used to load the program into the computer dedicated to data acquisition on the diesel engine.

There were two sets of requirements that the data acquisition and data reduction program were required to meet. One set of requirements determined what functions the program was to perform. The second set of requirements had to do with making the program "user friendly".

A. PROGRAMMING REQUIREMENTS

The basic functions of the program were to read a number of engine parameters, reduce them to a form that could be displayed to the user and use the recorded parameters to calculate additional quantities used in performance evaluations of the engine. Additionally, the program had to provide a means for the user to change the operating point

of the engine and provide a means of entering any data necessary for the calculations that could not be measured directly by the computer. Finally, the program had to display both the recorded and calculated variables and print a copy of the display if required by the user.

In order to meet all of the functional requirements the program needed to be written to run interactively. Since the program was to be used in a classroom laboratory environment it needed to be made as user friendly as possible. It would be used by students who would have virtually no time available to learn how the program operated. As a result, it had to be almost self-explanatory when installed and running. There was one additional requirement, not related to either of the other two broad sets of requirements that needed to be met by the programmer.

The Digital VT-103 computer when configured as the one in this experiment was, has an available memory of about 32K of 16-bit words. The only storage devices for programs were two internal cassette tape drives. The entire program had to reside in the computer memory that was available after the operating system was installed and memory partitioned for variable arrays necessary to the program. Since the drives operate very slowly, it was not practical to have a program so long that any subroutine would need to be called from a tape while the program was running.

B. PROGRAM STRUCTURE

The data acquisition and data reduction program was written as a set of subroutines, each designed to handle a series of related functional requirements. A short main program was written to allow the user to call each subroutine as required and to allow the user to exit the program if desired.

There were three main subroutines. One subroutine provided a means of inputting the values for four variables, not directly measurable by the computer, these were needed in the data reduction section of the program. A second subroutine allowed the user to change the RPM and load set points of the engine. The third subroutine performed the data acquisition and data reduction functions and displayed and printed the results.

A very short fourth subroutine was added after the program had been used for the first time by a class of students. The only function of this last subroutine was to read the engine RPM and torque and display the values on the terminal. This subroutine was provided as a convenience for the operator.

There was a separate menu associated with the main program and each subroutine that listed all of the options available to the user while in each subroutine. Commands were issued to the computer by typing the number of the option desired.

C. MAIN PROGRAM

When the computer is first powered up there is no operating system that automatically boots other than a simple machine language monitor. The RT-11SJ operating system is booted from a tape installed in one of the tape drives. After installation of the operating system, the data acquisition/data reduction program is loaded and run from the other tape drive by typing the command 'RUN DIESEL'.

The main program, which is entered when the program is first run, contains only a few lines of FORTRAN code. Its only function is to provide a starting point for user interaction with the program. It provides a means of calling the subroutines and a means of exiting the program.

The first menu, Figure 5, to appear on the screen is the menu associated with the main program. The program uses the prompt '>' anytime it is ready to receive a command through the keyboard. Commands are issued by simply typing the number of the option desired followed by <return>. Typing 1 <return> will call the subroutine that samples data and displays the results (subroutine RUN). Option 2 calls the subroutine that allows input of data through the keyboard (subroutine DATIN). Typing 3 allows the user to change engine RPM or load (subroutine ENGSET). Typing 4 ends execution of the program.

D. SUBROUTINE DATIN

There are four variables used in the data reduction portion of the program that are not measured directly by the computer. These variables must be entered by hand each time the program is run. There are no default values for these variables other than 0. The four variables are atmospheric pressure, specific gravity of the fuel, the temperature of the fuel sample and the diameter of the air inlet nozzle. The air inlet can be through one of two different size nozzles. When running the program this subroutine is usually the first subroutine called since subroutine RUN cannot be called until this data has been input.

Whenever this subroutine is entered, the menu shown in Figure 6 appears on the computer terminal. Typing 1 following the prompt will cause the computer to display, 'Enter new value for atmospheric pressure.'. The user types in the new value and the computer will rewrite the original DATIN menu with the new value for atmospheric pressure displayed. Typing 2, 3 or 4 will result in a similar response by the computer. Typing 5 will exit the subroutine.

E. SUBROUTINE ENGSET

The ENGSET subroutine has only one functiton, it allows the user to choose the operating point of the engine. To do this, the program must accept new set points, convert the

set points into values that can be used by the control computer and send the converted values to the control computer.

When entering this subroutine the following menu appears on the screen (Figure 7). Typing 1 or 2 allows the user to change the current values. After typing one of the first two commands the computer will display, 'Input an integer value for desired RPM (or torque).'. The user can then type in the new operating point. After entering the new point the computer will display the first menu again with the new value for either RPM or torque displayed. The computer also takes the new value and sends it to the control computer.

Before sending the new set point the computer must convert it to a value that can be passed over the simple parallel line interface connecting the two computers. The control computer uses an 8-bit microprocessor while the data acquisition computer uses a 16-bit microprocessor. A control computer 'word' is eight binary bits long while a data acquisition 'word' is sixteen binary bits long. As mentioned in Chapter 3, the two computers are interfaced by connecting the eight high order bits from the VT-103 parallel port to one of the eight bit parallel ports of the control computer and the eight low order bits to a second parallel port. One of the control computer parallel ports receives desired torque and one receives desired RPM, but

the 16-bit parallel port of the VT-103 has to send both desired torque and desired RPM at the same time.

An 8-bit word can be any decimal integer between 0 and 255. A 16-bit word can be any decimal integer between 0 and 65536. If the highest bit is used to indicate sign, a 16-bit word can be any integer between -32768 and +32768. The VT-103 operating system uses signed numbers so the second case applied in this instance. Desired torque and RPM are translated into integers between 0 and 32768 before being sent to the control computer. The program does this by first converting the desired RPM to an integer between 0 and 255 using equation 5.1.

$$R = 0.0755 * (\text{desired RPM}) \qquad \text{(eqn. 5.1)}$$

Desired torque is converted to an integer between 0 and 127 using equation 5.2.

$$L = 1.85 * (\text{desired torque}) \qquad \text{(eqn. 5.2)}$$

The integer value of desired torque (L) is then multiplied by 256. This has the same effect as shifting the binary value of the integer to the eight high bits of a 16-bit word. The two converted values are then added together and this value is written to the parallel port where it is

interpreted as two separate numbers by the control computer. The integer that is finally written to the parallel port is latched by both computers. This means that the number is not erased until another number is written to the port.

Every time a new value is entered by the user for desired RPM or desired torque the program rewrites the number in to the parallel port.

Option 4 of the subroutine command options allows the user to exit the RPM and load setting subroutine. Option 3 calls subroutine SPEED. This subroutine displays actual RPM and actual torque and then returns to the calling routine.

F. SUBROUTINE RUN

Subroutine RUN performs the most functions of all the routines and, as a result, is the longest and most complex portion of the entire program. The primary functions of the RUN subroutine are to read data from the analog-to-digital (A/D) converter and display the results. This subroutine performs all of the calculations needed to convert the output from the A/D converter to engineering units and to compute the parameters necessary for performance evaluations of the engine. Both the measured parameters, converted to engineering units, and the computed parameters are displayed on the terminal and can be printed by selecting one of the command options. Other command options allow the user to

display the raw output from the ADC with the standard deviation computed for each channel or to call the ENGSET of SPEED subroutines.

The subroutine RUN menu is shown in Figure 8. There are seven commands that can be given while this subroutine is executing.

Command option 1 will cause the program to read the first 12 channels of the A/D converter and performs the calculations necessary to convert the output to engineering units. It will also compute the performance parameters; brake, friction and indicated horsepower; mechanical and thermal efficiency; mean effective pressure, specific fuel consumption, scavenge ratio, air mass flow rate, and air-to-fuel ratio. Appendix E explains all of the equations used in these calculations. After performing the data acquisition and data reduction, the program will display the results on the VT-103 monitor. Figure 9 is a sample of the line-printer output. The terminal display is the same except that it includes a brief form of the command menu displayed below the output. A printed copy of the results can be obtained by issuing command 2.

Command 5 performs the same functions as command 1 (data acquisition and reduction) except that the terminal display is changed. The screen displays the mean and standard deviation of the raw data from each channel of the ADC. The

command 1 display can be obtained by issuing command 3. It is not possible to obtain a printed copy of the mean and standard deviations. Command 5 was used to calibrate the transducer output to the A/D converter.

Command 4 calls subroutine ENGSET. This command allows the user the option of changing the operating point of the engine without having to return to the main program first. Command 7 calls subroutine SPEED which displays the actual RPM and torque. Command 6 exits the subroutine.

VI. CONTROL THEORY

Prior to designing the control software a mathematical model of the engine and dynamometer transfer functions had to be developed using control theory and experimental data. Once the transfer functions were determined, appropriate control actions could be analytically tested.

A. DETERMINATION OF TRANSFER FUNCTIONS

A block diagram of the engine and dynamometer is shown in Figure 10 with the measureable parameters being the voltage applied to the throttle (V), throttle position (X), engine speed ($\dot{\theta}$), voltage to the dynamometer armature current controller (I) and dynamometer torque (T). Both the engine and dynamometer were modeled as first order systems. There were two additional characteristics of the engine that would conceivably need to be accounted for in the design of the control system; the time delay (transportation lag) of the engine and the effect of the throttle position control loop. Because of this, the throttle was also modeled as a first-order system and an exponential term, to describe the transportation lag, was introduced into the transfer function for the engine. Both the transportation lag and the effect of the transfer function of the throttle were

eventually determined to have a negligible effect on the design of the control system.

An open-loop first order transfer function has the form given in equation 6.1.

$$\frac{\dot{\theta}(s)}{E(s)} = \frac{K}{st + 1} \qquad \text{(eqn. 6.1)}$$

where K is the steady state gain constant and t is the time constant for the system. Both K and t can be experimentally determined for most systems. To determine K for the engine, the dynamometer load was set to zero and the voltage to the throttle was recorded for various engine speeds. During steady state operation, $K = \dot{\theta}/V$. Figure 11 lists the recorded data that was used to compute K. The average magnitude of K, with units of (1/volt-second), for the 14 data points is 71.3. This value was used in the initial analysis of the control problem.

While a value of K in units of (1/volt-sec) was convenient for the initial analysis, once the computer was installed it was easier to compute a value of K based on the decimal number output to the digital-to-analog converter and use the new value of K in further analysis. The value of the open loop gain constant computed by dividing engine RPM by D/A value is 13.2 RPM. This second value is what appears in subsequent calculations. A value for the K of

the dynamometer was computed in the same manner. The computed gain constant for the dynamometer is equal to 0.48 lbf-ft.

For a first order system, "t" is equal to 0.063 times the settling time (t_s) of the system after a step input. For the diesel engine t_1 was experimentally calculated by recording the response of the engine to a step input. Figure 12 shows a representative transient response curve of the engine to a throttle voltage change that corresponds to a change of roughly 200 RPM. A 2-pen strip chart recorder was used to record the transducer outputs for throttle position and engine speed. The transient response of the engine was recorded after a step change was made to the throttle voltage. No dynamometer load was applied to the engine for these measurements. The settling time, while found to vary somewhat depending on the initial engine speed, was determined to be approximately 120 seconds. This gave a time constant for the engine of approximately 75 seconds.

The time constant (T) associated with the transportation lag, while difficult to determine experimentally without the benefit of more sophisticated electronic equipment can be approximately determined analytically. Neto and Thaler [Ref. 6] showed that T could be approximated for a diesel engine by equation 6.2.

$$T = 40/RPM \qquad \text{(eqn. 6.2)}$$

The operating range of the General Motors diesel was 1500 to 2500 RPM. These speeds corresponded to time constants for the exponential term between 0.016 and 0.027 seconds. As a result, it could be assumed that the effects of transportation lag only become significant at frequencies higher than the operating range of the engine and that the effect of transportation lag can be neglected.

The time constant for the first order model of the throttle positioning loop was determined using the same technique as used to determine the time constant for the diesel engine. Settling time for the throttle positioning loop was less than 0.5 seconds. This gave a time constant for the throttle (t_2) of less than 0.315 seconds. As in the case of transportation lag, the response time of the throttle positioning loop can be ignored since it becomes significant only at frequencies higher than the operating frequencies of the engine.

The steady-state gain constant for the throttle cannot be ignored, but, because data was recorded for throttle voltage vs. RPM no additional calculations are required. The 13.2 RPM gain constant is in actuality the throttle gain constant multiplied by the engine gain constant. The final diesel engine transfer function for speed of the

engine as a function of the input to the throttle is given in equation 6.3.

$$\frac{RPM(s)}{E_1(s)} = \frac{13.2e^{-.02s}}{(75s + 1)(.315s + 1)} \qquad \text{(eqn. 6.3)}$$

The Bodie diagrams for the open loop transfer function of the diesel as determined experimentally is shown in Figure 12 and Figure 13 curve 1.

The same analysis was used to determine the transfer function of the dynamometer. For the dynamometer the armature current could be varied to control the torque applied to the engine. The magnitude of the load was a function of the voltage applied to the armature current controller. The open loop gain constant was experimentally determined at a constant engine speed of 1500 RPM.

The steady state dynamometer gain can be shown to be a function of engine RPM but for the purpose of this analysis was assumed to be a constant, 0.48 lbf-ft. The dynamometer had a calculated time constant that was very much smaller than the diesel engine. A plot of the transient response of the open loop transfer function was obtained in a manner similar to the method used to determine the time constant for the engine. A 2-pen strip chart recorder was connected to the voltage supply to the armature current controller and the dynamometer load sensor. The dynamometer had a settling

time of approximately 1.0 second which gave a time constant (t_3) of 0.63 seconds. The open loop transfer function for the dynamometer as determined experimentally is given in equation 6.4.

$$\frac{T(s)}{E_2(s)} = \frac{0.48}{(.63s + 1)} \qquad \text{(eqn. 6.4)}$$

The Bodie plots of the dynamometer transfer function are shown in Figures 14 and 15 curve 1.

B. DESIGN OF CONTROL ACTION

In designing the control action for both the engine and dynamometer the analysis was made assuming that the two systems were independent. A proportional-plus-integral-plus-differential control action was chosen for the controller. The use of a microprocessor allowed the use of any control action since the action depended only on the algorithm programmed into the computer and not on the system hardware. The PID controller offered several characteristics that were desirable in a control system.

A proportional controller has a function in the time domain of as shown in equation 6.5.

$$\dot{\theta}(t) = Ae(t) \qquad \text{(eqn. 6.5)}$$

In the Laplace domain the function was transformed into equation 6.6.

$$\frac{\dot{\theta}(s)}{E(s)} = A \qquad \text{(eqn. 6.6)}$$

The A in each function is an adjustable gain constant and allowed the programmer a method of adjusting the sensitivity of the control system.

The equation for an integral control action in the time domain is given in equation 6.7 for the time domain and in equation 6.8 for the Laplace domain.

$$\dot{\theta}(t) = B \int_0^t e(t)dt \qquad \text{(eqn. 6.7)}$$

$$\frac{\dot{\theta}(s)}{E(s)} = \frac{B}{s} \qquad \text{(eqn. 6.8)}$$

An integral control action has the characteristic of providing essentially zero steady state error to a control system. The integral of a small error between the actual operating point and the desired operating point will eventually become large enough to cause the system to return to the desired operating point. The "B" in the transfer function is a programmable gain associated with the integral control action.

A differential control action will respond only to a change in error and as a result can only be used in conjunction with a proportional or integral control action. It has the unique characteristic of only effecting a

response if the error in the controlled parameter is changing. This characteristic makes it impossible to use only a differential control action in a control system but when used in conjunction with one or both of the other control actions the controller can anticipate the approach of the system to the desired control point and slow the action of the controller. The function for a differential control action has the function in the time domain as shown in equation 6.9 and a function in the Laplace domain as shown in equation 6.10.

$$\dot{\theta}(t) = C \frac{de(t)}{dt} \qquad \text{(eqn. 6.9)}$$

$$\frac{\dot{\theta}(s)}{E(s)} = Cs \qquad \text{(eqn. 6.10)}$$

The constant C is a variable gain constant associated with the differential control action.

One additional approximation is required when a digital computer is installed in the feedback control loop. A digital computer does not compute the error, error integral and error differential continuously. The computer samples once during a discrete time period. In this application, the computer samples once every 0.54 seconds; the length of time it takes to complete one loop in the control program. The continuous functions for the integral and differential control actions are approximated by equation 6.11 and 6.12.

$$\dot{\theta}(t) = BT_s \sum_{n=0}^{t} e_n \qquad \text{(eqn. 6.11)}$$

$$\dot{\theta}(t) = \frac{C}{T_s}(e_n - e_{n-1}) \qquad \text{(eqn. 6.12)}$$

Combining the three control actions gives an 's' domain function as given in equation 6.13.

$$\frac{\dot{\theta}(s)}{E(s)} = A + \frac{BT_s}{S} + \frac{C}{T_s} S \qquad \text{(eqn. 6.13)}$$

A small amount of algebraic manipulation puts the function in Bodie form (equation 6.14).

$$\frac{\dot{\theta}(s)}{E(s)} = \frac{T_s B \left(\frac{C}{BT_s^2} S^2 + \frac{A}{BT_s} S + 1 \right)}{S} \qquad \text{(eqn. 6.14)}$$

The steady state gain constant for the function in Bodie form now becomes $B*T_s$. The natural frequency associated with the controller (ω) is equal T_s*sqrt(B/C) and the damping ratio for the controller (δ) is equal to,

$$A/sqrt(4*B*C) \qquad \text{(eqn. 6.15)}$$

The T_s in each equation represents the sample time period; the time the control computer takes to make one iteration of the control loop. For this system T_s = 0.54 seconds.

The Bodie diagram for the diesel engine PID controller are shown in Figure 12 and Figure 13 curve 2. The Bodie plots for the dynamometer are given as curve 2 of Figures 14 and 15.

The initial design of the controller necessitated determining values for the three constants associated with a PID controller (A, B and C). These constants were originally determined analytically but their final values were obtained experimentally by monitoring the performance of the system with the control computer installed.

The open loop Bodie plots for the compensated diesel engine are shown in Figures 12 and 13 curve 3. These are the diagrams of the system in its final form. The objective in designing the system was to provide an open loop gain margin of at least 5 dB and a phase margin of approximately 45 degrees. In both cases the margins were exceeded. The final values for the three constants for the diesel engine speed control were A=1, B=0.0125, and C=5. For the dynamometer load controller the values were A=0.04, B=0.004, and C=0.2. As stated previously, Figures 12 and 13 show the Bodie plots of the uncompensated and compensated diesel engine and the diesel engine controller transfer functions. A block diagram for the controlled diesel engine and dynamometer showing all of the transfer functions is shown in Figure 16. The Bodie plots for the compensated

dynamometer transfer function are given in Figures 14 and 15 curve 3 along with the uncompensated dynamometer and the dynamometer controller transfer functions.

VII. CONTROL SOFTWARE

The control software that is installed in the SYS-1 computer is written entirely in interpreted NSC Tiny BASIC. The control algorithm is very easy to program in BASIC and requires only a few lines of code. In the final program limits are placed on the numerical value of certain program variables to prevent register overflow and to lessen the impact of system noise on the response of the system

The basic coding of the control algorithm requires only 7 lines of programming.

```
10 E=R-M
20 I=I+E
30 D=E-E1
40 E1=E
50 V=A*E+B*I+C*D
60 N=N+V
70 GOTO 10
```

In the above example, the error (E) is determined at line 10 by subtracting the measured value (M) for a controlled parameter from the requested value (R). In line 20 a numerical integration is performed by adding the current

error to the error total from all previous iterations. Line 30 performs a numerical differentiation by subtracting the error from the previous iteration from the current error. The numerical values for the error, error integral and error differential are multiplied by their respective gain constants (A, B and C) and added together to give a numerical value representing the change (V) in the output to the actuator (N). In line 60 the change is added to the existing value and line 70 returns the program to line 10 to begin another iteration. The actual control program is not quite so simple. All further comments on the control program refer to the listing of the actual control program found in Figure 17.

The explanation of the program installed in the SYS-1 begins at line 100. Actual engine speed and load are input through channels 5 and 8, respectively, of the analog-to-digital converter. Channel 5 is located at address #9804 and channel 8 is located at address #9808. NSC Tiny BASIC supports most of the commands found in Dartmouth BASIC but many require a shortened code. A listing of the format for Tiny BASIC commands can be found in the SYS-1 User's Guide [Ref. 3]. In addition to only using Tiny BASIC as a higher level language, the SYS-1 can only perform integer arithmetic.

The @ command in Tiny BASIC performs the same functions as PEEK and POKE in standard BASIC. The '#' sign indicates a number is a hexidecimal number. The explanation of the code begins at line 100 which reads the actual values for engine RPM and engine load. The analog-to-digital converter must be written to in order to begin a conversion, so 0 is written to addresses #9804 and #9808 prior to reading from addresses #9804 and #9808. The ADC requires 8 clock cycles to perform one conversion. This is less time than it takes the microprocessor to interpret the next command so there is no danger of attempting to read a channel prior to the completion of a conversion.

Requested values for engine RPM and torque are read at line 110. Addresses #0A00 and #0A01 are the locations for Port A and Port B of the SYS-1 computer's installed peripheral interface adapter (PIO). These two ports are used to interface the SYS-1 to the parallel line interface of the VT-103 data aquisition computer. Due to the configuration of the VT-103 operating system, the largest integer number that can be transferred through Port B is 127. Because of this, the value received at register #0A00 is multiplied by 3 to increase its value to the same range as that read at register #9808.

If the value for requested RPM is less than 10 (10 corresponds to approximately 100 RPM), the program jumps to

line 10 for execution. Lines 10, 20 and 30 form a secondary loop outside the main program that stops execution of the control algorithm until a value greater than 10 is input through the PIO. This secondary loop smooths the transition from manual to computer control of the engine and dyna-momter. Prior to returning to the main program the error integrals are re-initialized and the current engine RPM is read and the value for engine RPM is written to the register controlling throttle position.

Lines 120 through 170 determine the control action of the computer and output to the actuators. There are 10 IF-THEN statements within this portion of the program which serve to limit the magnitude of the absolute value of certain variables. These statements prevent some variables from overriding others and producing adverse effects in the control action and also prevent overflow errors from occurring in the registers associated with the digital-to-analog (D/A) converters.

Limits are placed on the error integrals and output for both the RPM and torque actuators. In addition a limit is placed on the magnitude of the change that can be output to the throttle position between any two successive iterations of the engine speed control algorithm.

The limit on V, the change in throttle position, protects the system from spurious conversions by the ADC due

to electrical noise. During system operation, it was noticed that occasionally inconsistent readings would be received by the computer from the ADC. The engine would be running at a steady RPM and suddenly, during one iteration, the computer would read an error of several hundred RPM. The error invariably returned to a value consistent with previous iterations on the following iteration but the transient behavior of the system due to the spurious reading could be quite unsatisfactory, requiring a minute or more to return to steady state, if the magnitude of V were not limited.

The value of the integral term in the control equation is greatest when the system is operating close to its desired control point. The integral term always returns the system to the precise control point requested within the accuracy the controller can measure. The disadvantage of the integral term occurs when the system is slow to respond to a change to the control point. As an example, the diesel engine will react slowly to a speed change if it is operating under a heavy load. In this case if the error integral is not limited it can become very large and the system will steady out at a point above or below the control point until the magnitude of the error integral is reduced to near zero. Limiting the magnitude of the error integrals prevents this type of undesirable system response.

The last set of variables artifically limited by the program are the variables output to the actuators. These variables are written to a PIO which sends the digital equivalent of the variable to the D/A converters to be converted into analog voltages. The value of the variables written to the D/A converters is limited to integers between 0 and 255. The 8-bit DACs used in this system cannot convert integers outside this rangee.

Line 180 prints the current values for all variables prior to the program returning to line 100 to state another iteration. While this line is not necessary for the operation of the system it aids in designing and fine tuning the program and presents a visual representation of the transient behavior of the system.

VIII. RESULTS AND CONCLUSIONS

The integrated data acquisition and data reduction system and engine control system meet all of the system criteria but both systems could benefit from further development. After manually starting the engine, speed and load control could be passed to the control computer and the entire range of experiments run in class could be performed using the data acquisition computer. The operator was able to change engine RPM and load, measure data and output data using the computer keyboard. Improvements could be made in two areas of each system (control system and data acquisition system). Improvements in resolution and transient response could be made to the control system and improvements in data storage and in the calculation of one of the performance parameters of the engine could be made in the data acquisition system.

A. CONTROL SYSTEM

The diesel engine control system will only maintain engine RPM and load within the resolution of the 8-bit analog-to-digital converter. The maximum theoretical resolution of the converter in RPM is,

$$\pm(1/255) \times 2500 = \pm 9.8 \text{ RPM} \qquad \text{(eqn. 8.1)}$$

This resolution could be obtained if the RPM sensor output +5 volts when the engine was operating at its maximum speed (2500 RPM). The actual measured resolution is +13.1 RPM. As a result of the poor resolution of the engine speed, the controlled engine speed will fluctuate around the desired RPM. This characteristic of the control system appears aggravated when the engine is operating at high speeds.

The problem could be alleviated by using a 12-bit A/D converter in place of the 8-bit converter. A 12-bit converter would have a theoretical resolution of,

$$\pm(1/4096) \times 3000 = \pm 0.6 \text{ RPM} \qquad \text{(eqn. 8.2)}$$

This resolution would allow much more precise control of engine speed.

Using the 8-bit converter to control engine load does not create the same problems as it does with speed control. The theoretical resolution of the 8-bit A/D converter when measuring torque is $\pm$0.2 lbf-ft. The actual measured resolution is $\pm$0.5 lbf-ft. which is well within the acceptable error in torque for the experiments.

The second characteristic of the control system that would benefit from further development is the transient response of the controlled system. The engine exhibits an overshoot of approximately 10% when responding to a step

change to desired RPM. This overshoot occurs both when the engine is accelerating or decelerating. The transient response characteristics of the controlled system could be improved by optimizing the values of the three constants associated with each controller.

A more accurate mathematical model of the transfer functions for the engine and dynamometer would aid in optimizing the control system. In the transfer functions, the steady state gain of each system is not a constant. The gain of the engine is a function of torque (K = k(T)) and the gain of the dynamometer is a function of RPM (K = k(RPM)). A refined form of the diesel engine transfer function is given in equation 8.3 and a refined form of the dynamometer transfer function is given in equation 8.4

$$\frac{RPM(s)}{E_1(s)} = \frac{k(T)e^{-\tau s}}{(t_1 s + 1)(t_2 s + 1)} \qquad \text{(eqn. 8.3)}$$

$$\frac{T(s)}{E_2(s)} = \frac{k(RPM)}{(t_2 s + 1)} \qquad \text{(eqn. 8.4)}$$

In the two equations, k(T) and k(RPM) can be experimentally determined.

B. DATA ACQUISITION SYSTEM

The biggest problem with the data acquisition and data reduction system is due to the lack of data storage

capacity. The VT-103 tape drives operated so slowly that it was impractical to store data on tape when running experiments. The system needed a disk drive for faster data storage and access. The slow speed of the tape drives also caused undesirable delays when running the program. Using the installed tape drives required ten minutes to boot the operating system and load and run the data acquisition program. Anytime the user required a printout of the data, a delay of 2.5 minutes was experienced while the program called a system subroutine from the system library stored on tape. A disk drive installed in the system would have alleviated all of these problems.

The second area for future development in the data acquisition system is in the computation of engine frictional horsepower. This is the horsepower the engine expends in overcoming internal friction and in powering auxiliary equipment such as the oil pump. The program calculated friction horsepower by using a curve fit to the results of prior experiments. The data for the curve fit was obtained by rotating the engine with the throttle closed using the dynamometer as an electric motor and recording the generated torque. While this curve appears reliable under most conditions it can give unreliable results if engine characteristics, such as operating temperatures, change. A subroutine needs to be written which will power the engine

with the dynamometer and record the torque as a function of engine RPM. The program could then fit a curve to the acquired data that would give a more accurate representation of engine friction horsepower for any given series of experiments.

A last comment is needed on the calibration of the analog-to-digital converter channels. Because of time constraints, accurate calibrations were not made for any of the A/D channels. Instead, the transducers were left installed and the values read from the converter channels were compared to the values read on the existing gages. A range of values was recorded for each channel by operating the engine through a variety of speed and load conditions. The readings recorded from the existing gages could not be as accurate as desired because the recorded engine parameters tend to fluctuate while the engine is operating at any given operating point. A more accurate calibration of the analog-to-digital converters is desired.

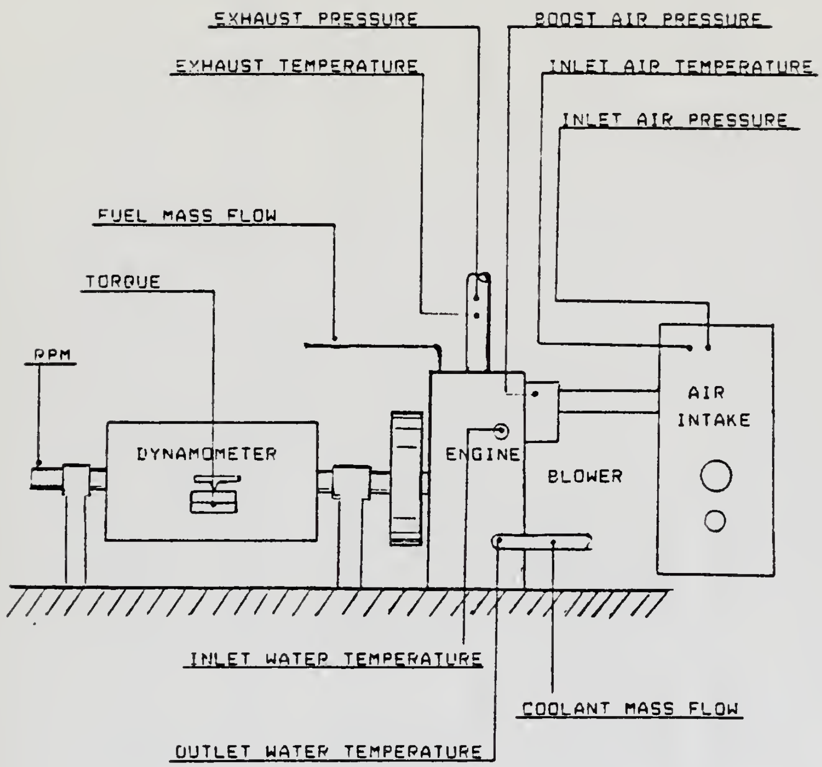
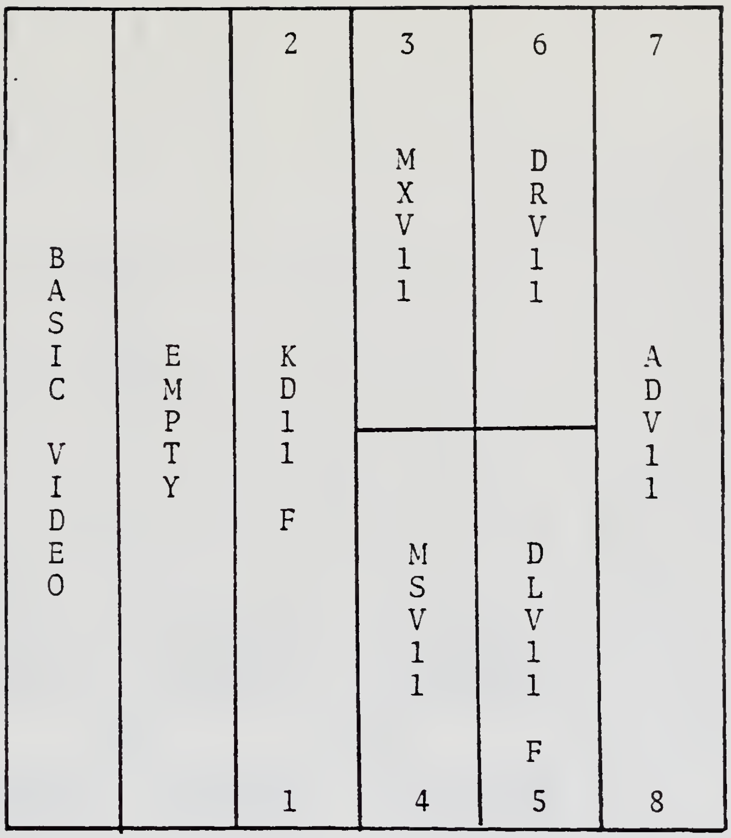


Figure 1. Machinery Layout; Engine, Dynamometer, and Transducers



KD11-F -- M7264 LSI-11 CPU with 4K RAM

MXV11 -- M8047 Multifunction module

MSV11 -- M8044 32K X 16-bit MOS memory

DLV11-F -- M8028 Asynchronous line unit interface

DRV11 -- M7941 Parallel line unit interface

ADV11 -- A012 16-Channel, 12-bit A/D converter

Figure 2. Configuration of VT-103 Backplane

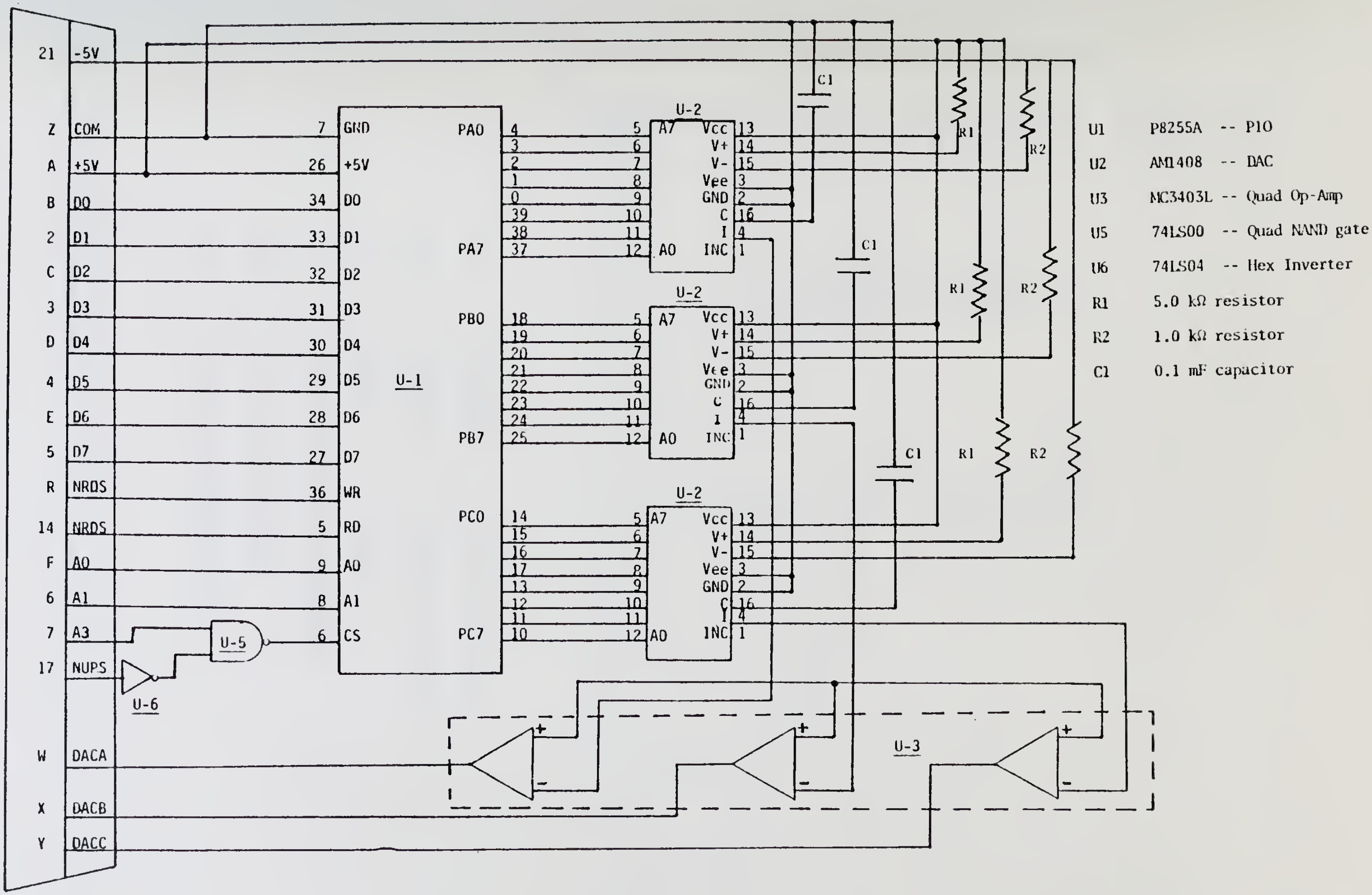
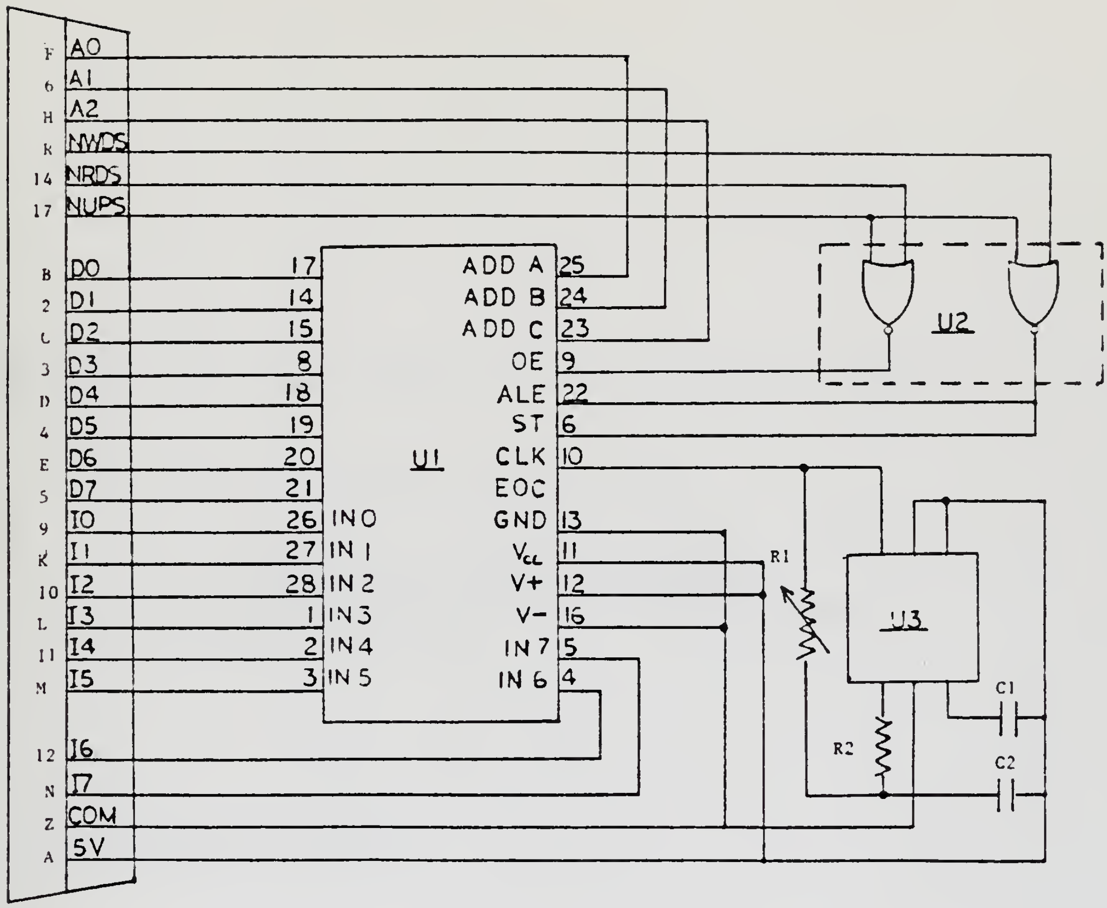


Figure 3. Schematic of 8-bit Digital-to-Analog Converter



U1	ADC0809	--	A/D Converter
U2	74LS02	--	Quad NOR gate
U3	LM555	--	Timer
R1	100 kΩ potentiometer		
R2	1.0 kΩ resistor		
C1	0.01 mF capacitor		

Figure 4. Schematic of 8-bit Analog-to-Digital Converter

```
DIESEL ENGINE DATA AQUISITION AND CONTROL PROGRAM

        Current command options are:

        1. Data acquisition and display subroutine.
        2. Input data through Keyboard.
        3. Engine RPM and load setting subroutine.
        4. Exit program.



 Enter desired option.
>
```

Figure 5. Data Acquisition Program Main Command Menu

```
CONSTANT PARAMETERS

Options 1 through 4 allow entering the parameters that remain
constant during data reduction. Typing 5 returns the user to
the calling subroutine.


   1. ATMOSPHERIC PRESSURE             0.00 in. Hg
   2. FUEL SAMPLE SPECIFIC GRAVITY 0.0000
   3. FUEL SAMPLE TEMPERATURE         0.000 deg. F
   4. NOZZLE DIAMETER                 0.000 in.
   5. Return

Enter desired option.
>
```

Figure 6. Subroutine DATIN Command Menu

```
ENGINE SPEED AND LOAD SET

Current values;   RPM =     0   TORQUE =  0Ft.lbs.

          Current command options are;

          1. to change engine RPM
          2. to change engine load
          3. to return
          4. to display RPM and load


Enter desired option.
>
```

Figure 7. Subroutine ENGSET Command Menu

```
DATA AQUISITION AND REDUCTION

          Current command options are;

          1. Begin data acquisition and display results.
          2. Print copy of displayed data on the lineprinter.
          3. Display the results of the last run.
          4. Change RPM or Torque
          5. Display mean and std. deviation
          6. Return
          7. Display RPM and Torque

Enter desired option
>
```

Figure 8. Subroutine RUN Command Menu

RUN NO. 18
RPM = 2248.5   TORQUE = 52.38

Measured Parameters		Computed Parameters	
Atmospheric temp.	67.2 deg F	Brake Horsepower	22.4 HP
Exhaust Temp.	890.0 deg F	Friction HP	16.3 HP
Coolant inlet temp	163.3 deg F	Indicated HP	38.7 HP
Coolant outlet temp	18.7 deg F		
Fuel temp	64.2 deg F	Mechanical efficiency	0.5793
Atmospheric press.	30.240 in Hg	Thermal efficiency	0.2374
Inlet air pressure	1.226 in H2O	Mean effective press.	74.42 psia
Boost air press.	9.90 in Hg	SFC (lbm/hp-hr)	0.587
Exhaust gas press.	11.52 in H2O	Scavenge ratio	1.26
Fuel mass flow rate	0.00366 lbm/s	Air mass flow rate	0.12 lbm/s
Coolant mass flow	2082.70 lbm/s	Air/Fuel ratio	32.541

Figure 9. Sample Printed Output from Data Acquisition Program

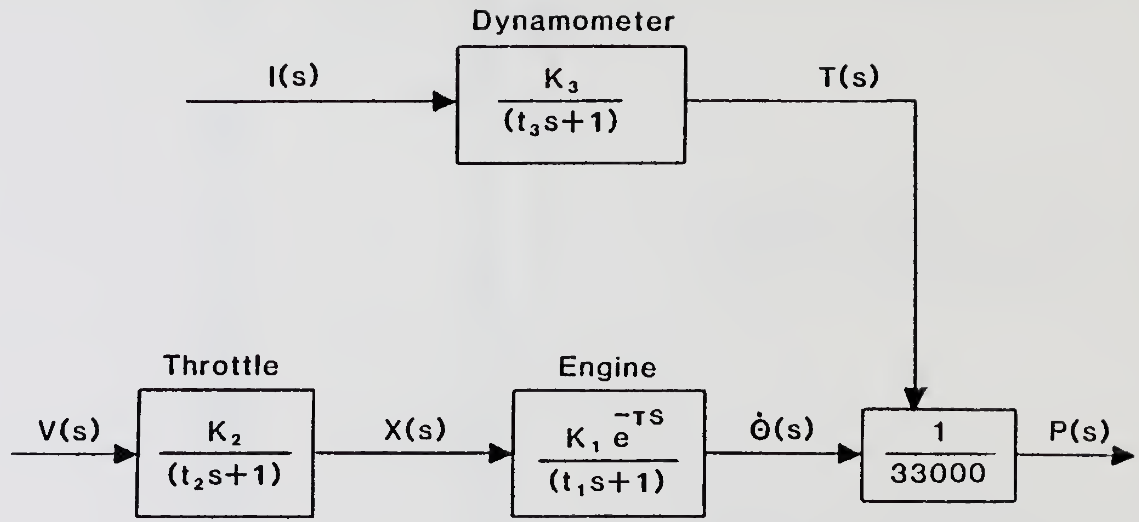


Figure 10. Open Loop System Block Diagram

Engine RPM	$\dot{\theta}$ (rad/sec)	V (volts)	K (1/volt-sec)
510	53.41	0.755	70.7
1000	104.72	1.471	71.2
1500	157.08	2.260	69.5
2010	210.49	2.960	71.1
2300	240.86	3.180	75.8
2490	260.75	2.670	71.0
2000	209.44	2.940	71.2
1520	159.17	2.230	71.4
1500	157.08	2.210	71.1
1230	128.81	1.873	71.0
1000	104.72	1.510	69.4
920	96.34	1.358	70.9
550	57.59	0.778	74.0

Average value of K = 71.4

Determined at no load conditions.

Figure 11. Data for Determination of Engine Gain Constant

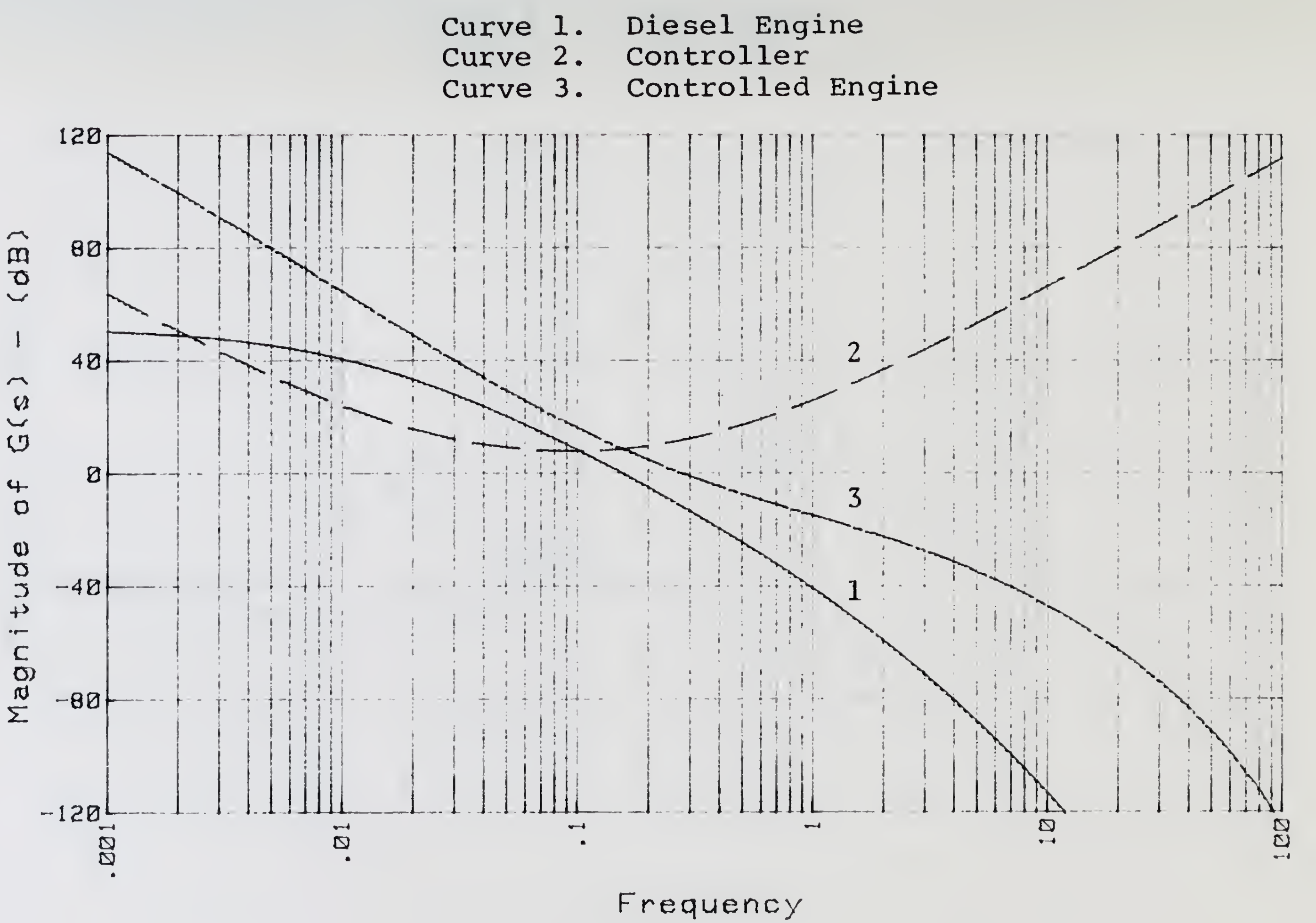


Figure 12. Diesel Engine Frequency Response Curves--Log Magnitude of G(jω)

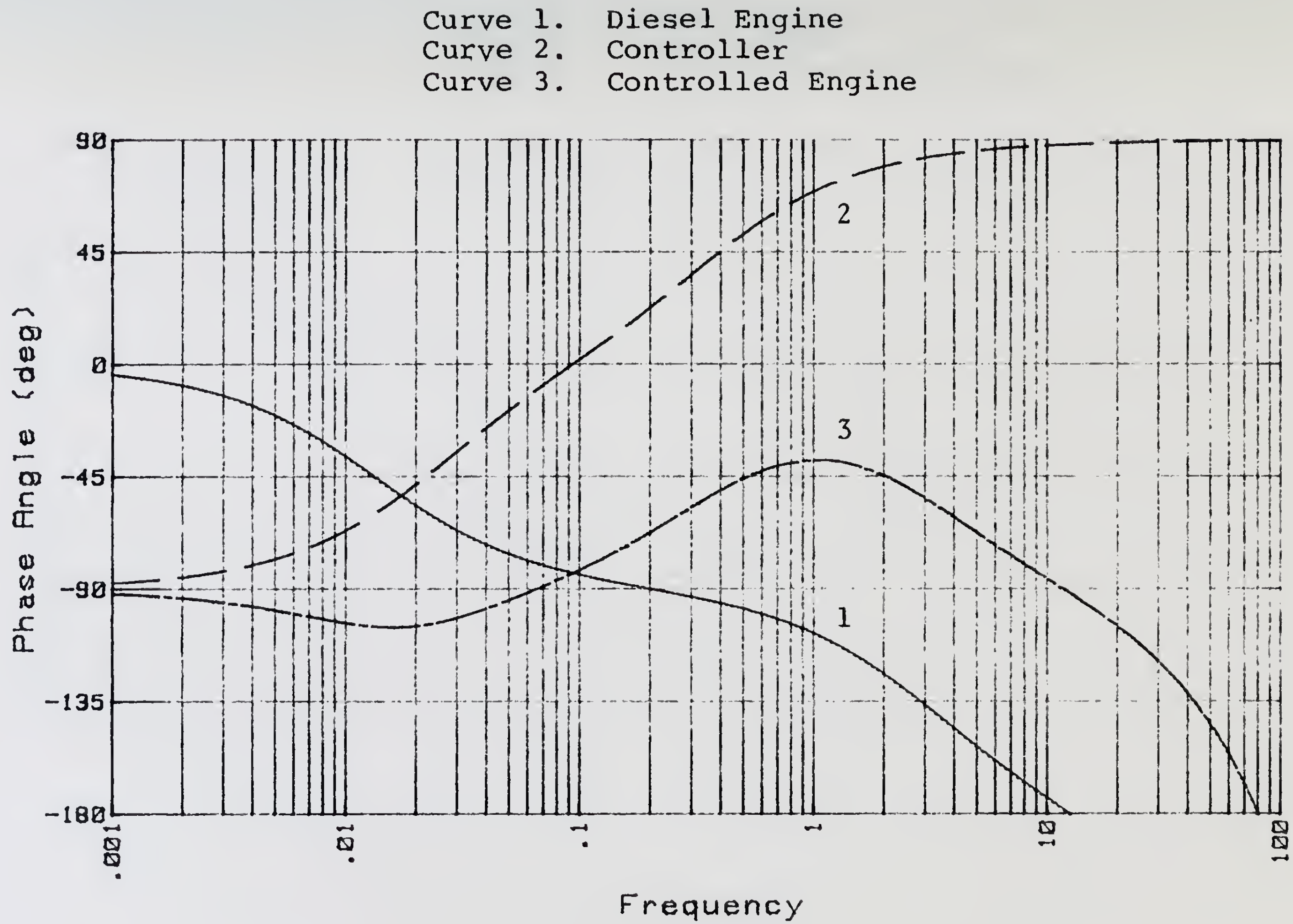


Figure 13. Diesel Engine Frequency Response Curves--Phase Angle of G(jω)

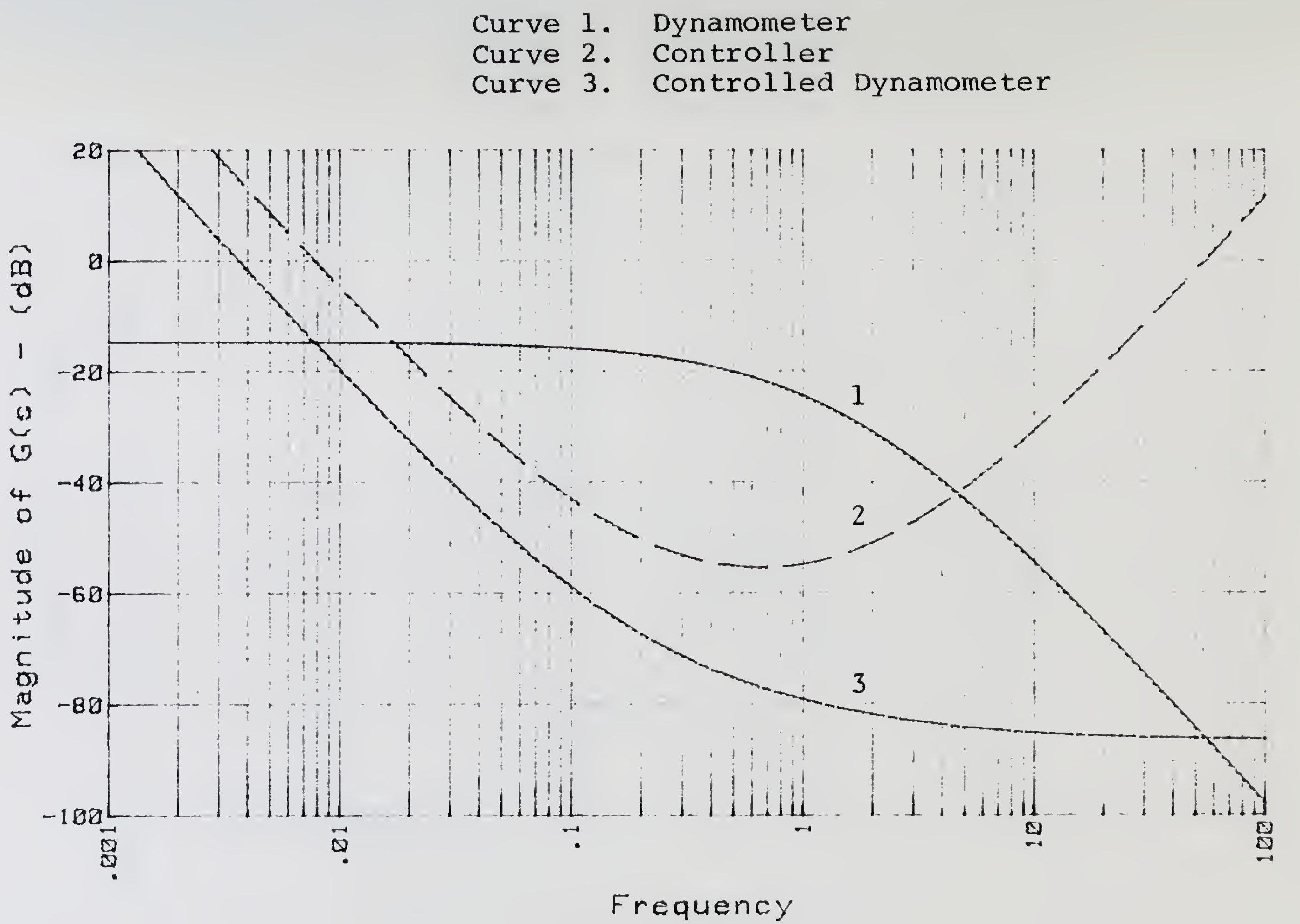


Figure 14. Dynamometer Frequency Response Curves--Log Magnitude of G(jω)

Curve 1. Dynamometer
Curve 2. Controller
Curve 3. Controller Dynamometer

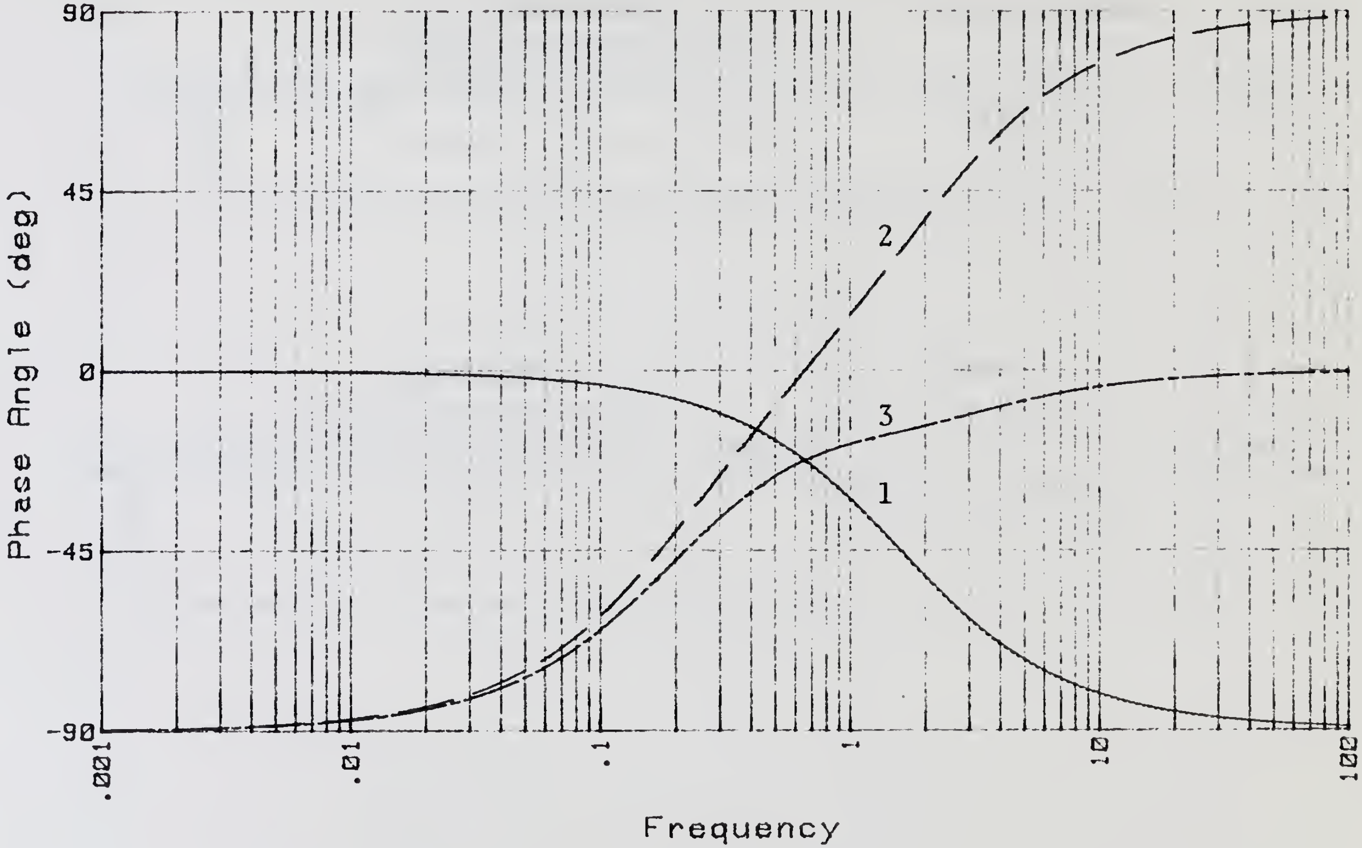


Figure 15. Dynamometer Frequency Response Curves--Phase Angle of G(jω)

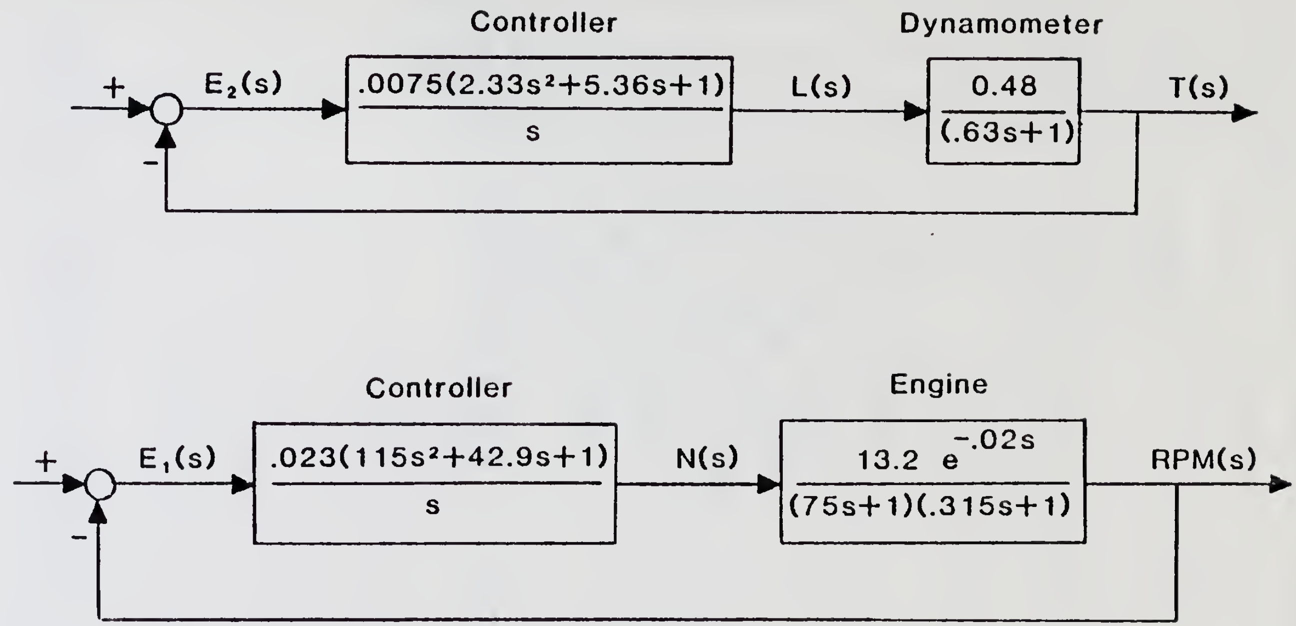


Figure 16. Closed Loop System Block Diagram

```
1 REM: DIESEL ENGINE CONTROL PROGRAM
5 @#980B=#80
10 PRINT "CONTROL PROGRAM"
20 R=@0A00
25 @#9804=0:N=@#9804
30 IF (R<10) GOTO 20
40 @#9808=N:I=0:A=0
100 @#9804=0:M@#9804:@#9807=0:X=@#9807
110 R=@#0A00:T=3*@#0A01
120 IF (R<10) GOTO 10
130 E=R-M:Y=T-X:I=I+E:A=A+Y:D=E-F:G=Y-Z
131 V=E+I/80+5*D
131 IF (V>50) THEN V=50
132 IF (V<-50) THEN V=-50
140 J=(Y+A/20+5*G)/25
145 IF (I>200) THEN I=200
146 IF (I<-200) THEN I=-200
147 IF (A>150) THEN A=150
148 IF (A<-150) THEN A=-150
150 F=E:Z=Y:N=N+V:L=L+J
160 IF (N>255) THEN N=255
161 IF (N<0) THEN N=0
162 IF (L>255) THEN L=255
163 IF (L<0) THEN L=0
170 @#9808=N:@#9809=L
180 PRINT E,I/80,5*D,V,N,"      ",Y,A/20,5*G,J,L
190 GOTO 100
200 END
```

Figure 17. Control Program for SYS-1 Computer

APPENDIX A

EQUIPMENT AND INSTRUMENTATION

Table A.1

Engine:	GM Model 1-53X3 2 stroke cycle Roots 3 lobe blower 30 BHP at 3000 RPM
Dynamometer:	Reliance Super T DC motor Frame 366-A-DZ, 30 HP Serial number U 302715-71
RPM:	Anadex Panel Meter Counter Model CPM-603, ser. 43911 0 to 99999 RPM note 1.
Torque:	Wallace and Tiernan Model FA 145 Serial number DD 08995 Scale 0-70 and 70-125 lbf-ft note 2.
Exhaust Gas Pressure:	Celesco LCVR Differential Pressure Transducer with LCCD Carrier Demodulator Range 0-25 cm H20 0-5 volts DC output
Inlet Air Pressure:	Celesco LCVR Differential Pressure Transducer with LCCD Carrier Demodulator Range 0-25 cm H20 0-5 volts DC output
Boost Air Pressure:	Celesco LCVR Differential Pressure Transducer with LCCD Carrier Demodulator Range 0-100 cm H20 0-5 volts DC output

Fuel Mass Flow Rate:	Anadex Panel Meter Counter Model CPM-603, ser. 43913 note 1.
Fuel Temperature:	Newport Pyrometer Model 268TF1,05,CC2 Serial 99180149-25 Scale 0-999.99 deg F Output 0.001 volts/deg F
Exhaust Gas Temperature:	Newport Pyrometer Model 268TF1,05,CC2 Serial 9108656-25 Scale 0-999.99 deg F Output 0.001 volts/deg F
Inlet Air Temperature:	Newport Pyrometer Model 268TF1,05,CC2 Serial 9180154-25 Scale 0-999.99 deg F Output 0.001 volts/deg F
Water Temperature In:	Newport Pyrometer Model 268TF1,05,CC2 Serial 9180150-25 Scale 0-999.99 deg F Output 0.001 volts/deg F
Water Temperature Out:	Newport Pyrometer Model 268TF1,05,CC2 Serial 9180151-25 Scale 0-999.00 deg F Output 0.001 volts/deg F

Note 1. - The Anadex meters used to measure RPM and fuel mass flow have variable frequency output signals. Instrumentation amplifiers were constructed locally to convert the frequency output to voltage output in the range of 0-5 volts DC.

Note 2. - The Wallace and Tiernan torque meter measures torque by sensing the air pressure developed by a bellows attached to a lever arm that positions the dynamometer. A Celsco LCVR differential pressure transducer and LCCD carrier demodulator were inserted in parallel with the torque meter to sense the bellows air pressure. Output from the LCVR was converted to lbf-ft torque by comparing it to the existing torque.

APPENDIX B

DATA FOR CALIBRATION OF THE ANALOG-TO-DIGITAL CONVERTER

Table B.1. Channels 1-5, Temperature

Digital Value	Deg F

Resolution = 2.5 deg F

Table B.2. Channel 7, Inlet Air Pressure

Digital Value	IN H20

Resolution = 0.004 in H20

Table B.3. Channel 8, Boost Air Pressure

Digital Value	IN Hg

Resolution = 0.02 in Hg

Table B.4. Channel 9, Exhaust Gas Pressure (PEXH)

Digital Value	IN H20

Resolution = .005 in H20

Table B.5. Channel 10, Fuel Mass Flow Rate (MFUEL)

Digital Value	lbm/sec

Resolution = .000004 lbm/sec

Table B.6. Channel 12, Engine Speed (RPM)

Digital Value	RPM

Resolution = 0.03 lbf-ft

Table B.7. Channel 13, Engine Torque (TORQ)

Digital Value	lbf-ft

Resolution = 2.0 RPM

APPENDIX C

CALIBRATION CURVE PLOTS

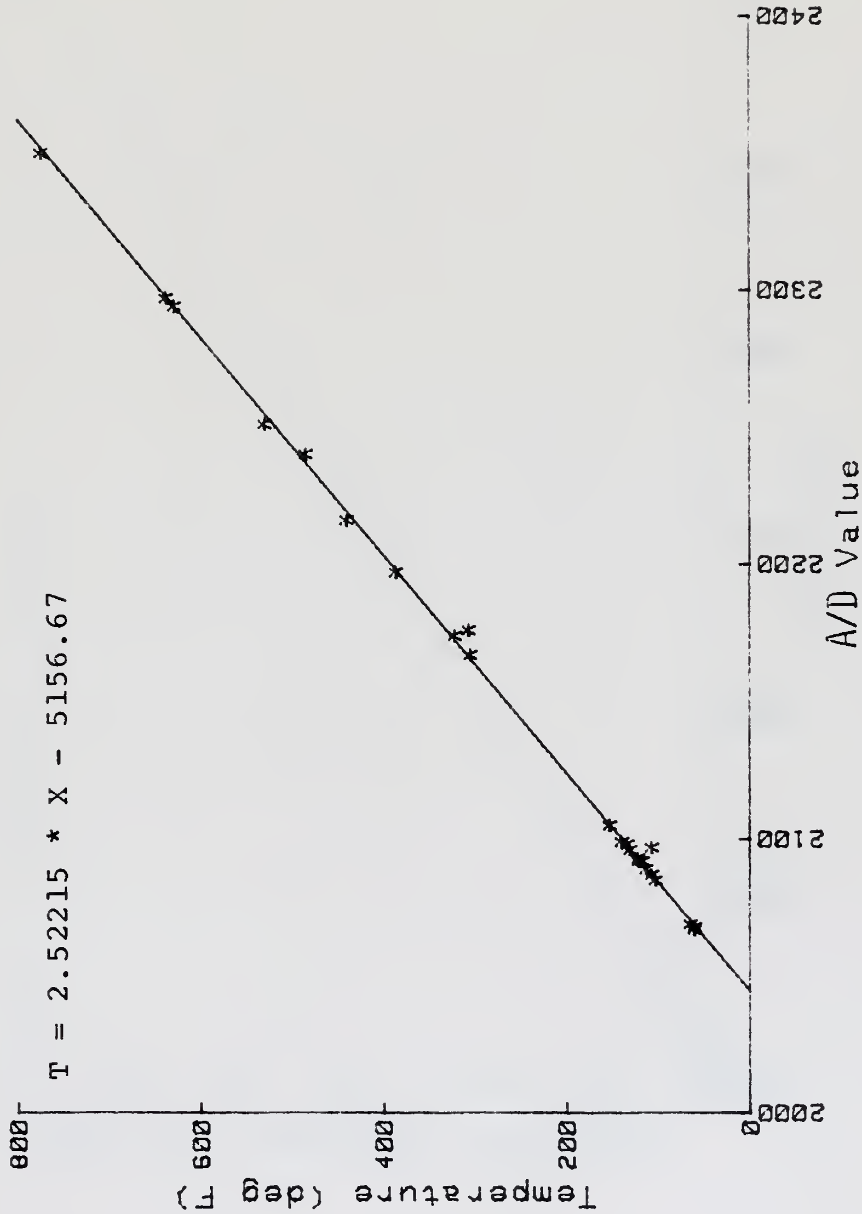


Figure C.1. Temperature Calibration Curve and Data Points

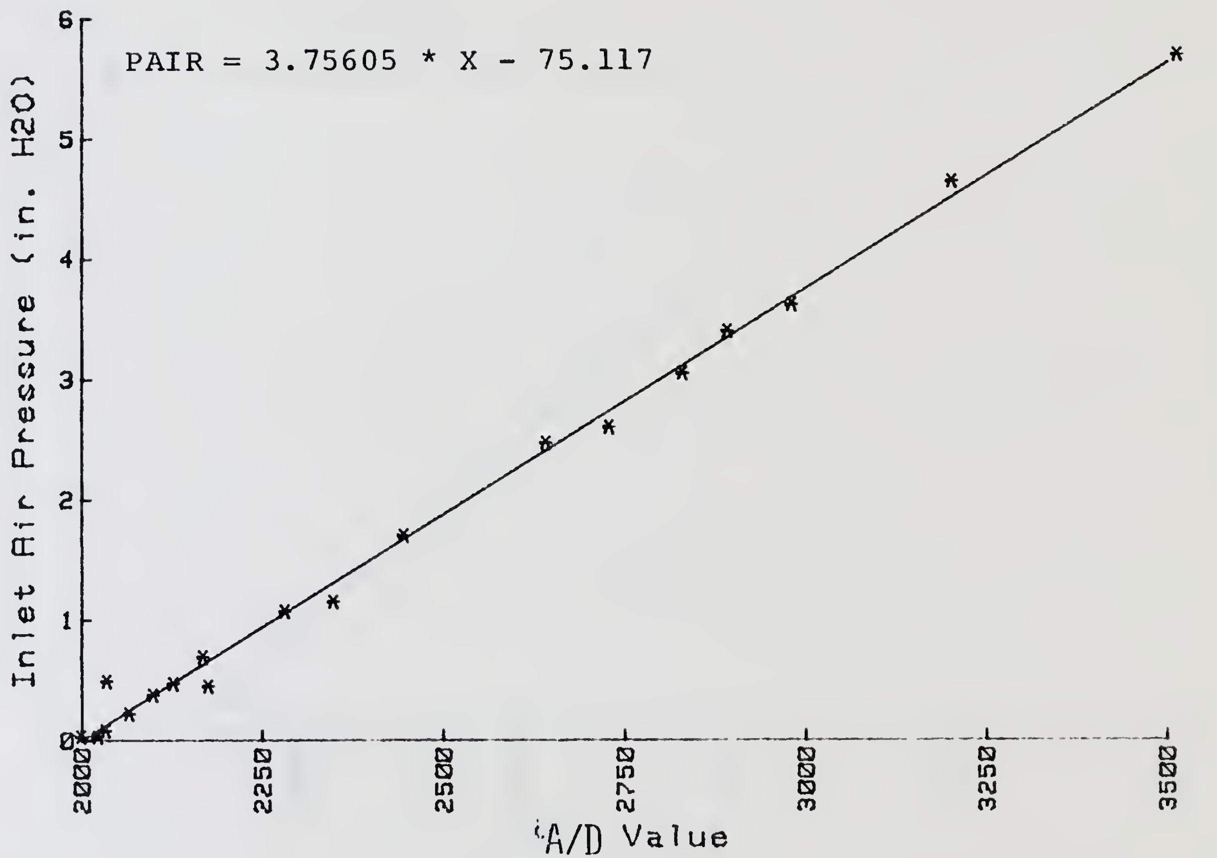


Figure C.2. Inlet Air Pressure Calibration Curve and Data Points

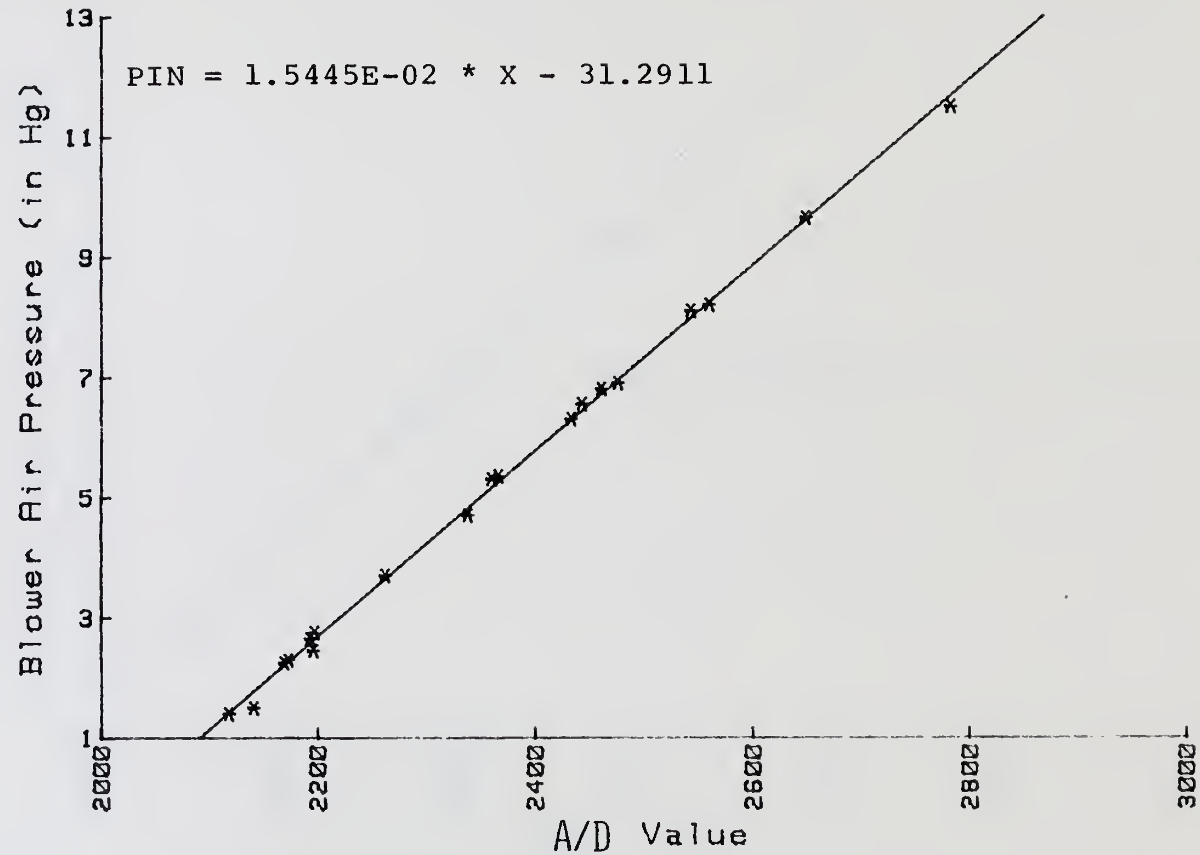


Figure C.3. Boost Air Pressure Calibration Curve

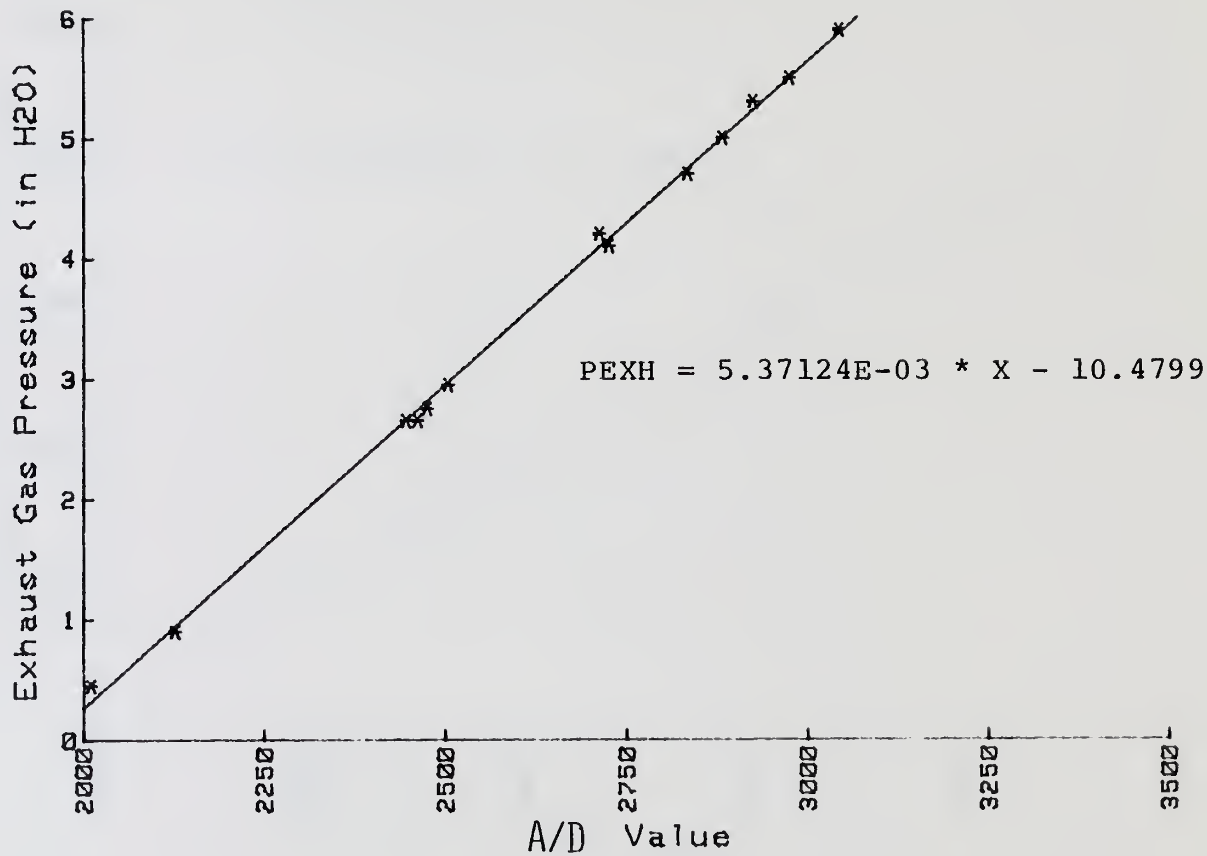


Figure C.4. Exhaust Gas Pressure Calibration Curve

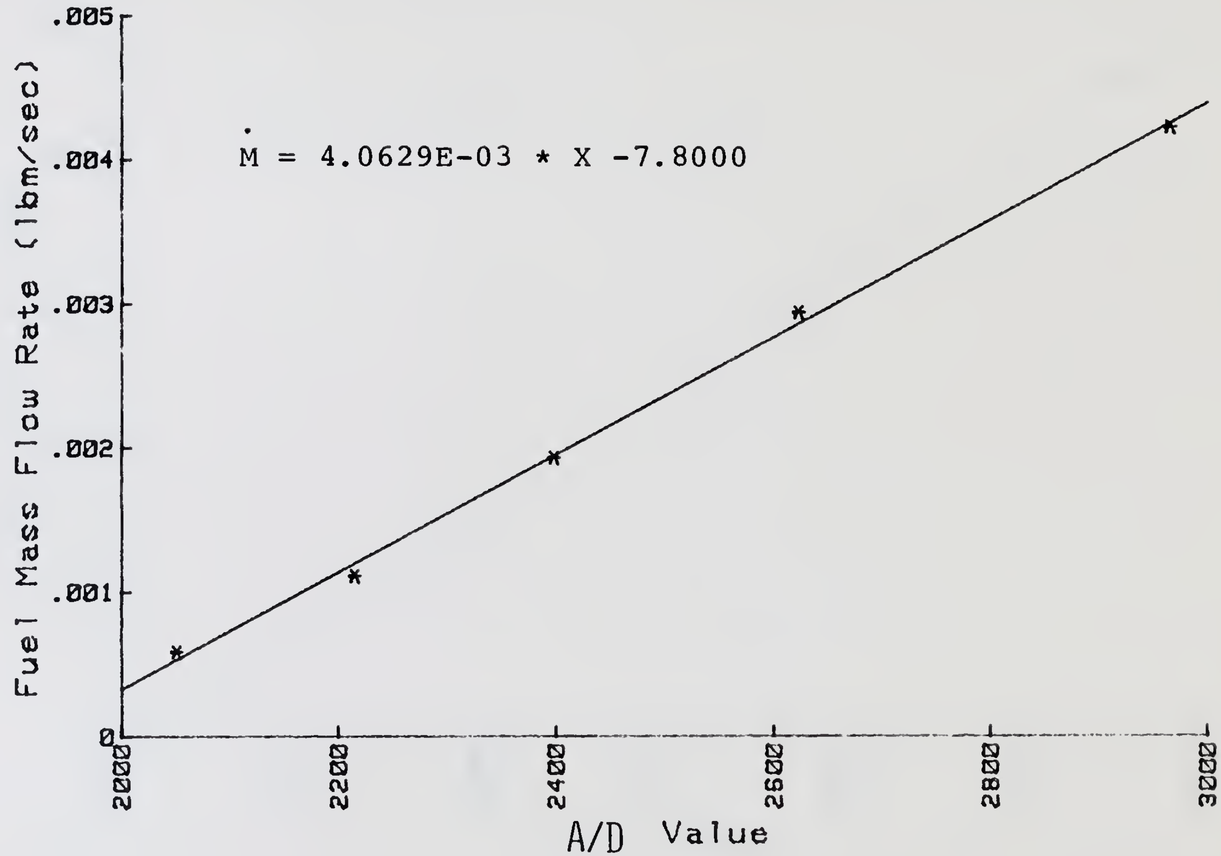


Figure C.5. Fuel Mass Flow Rate Calibration Curve

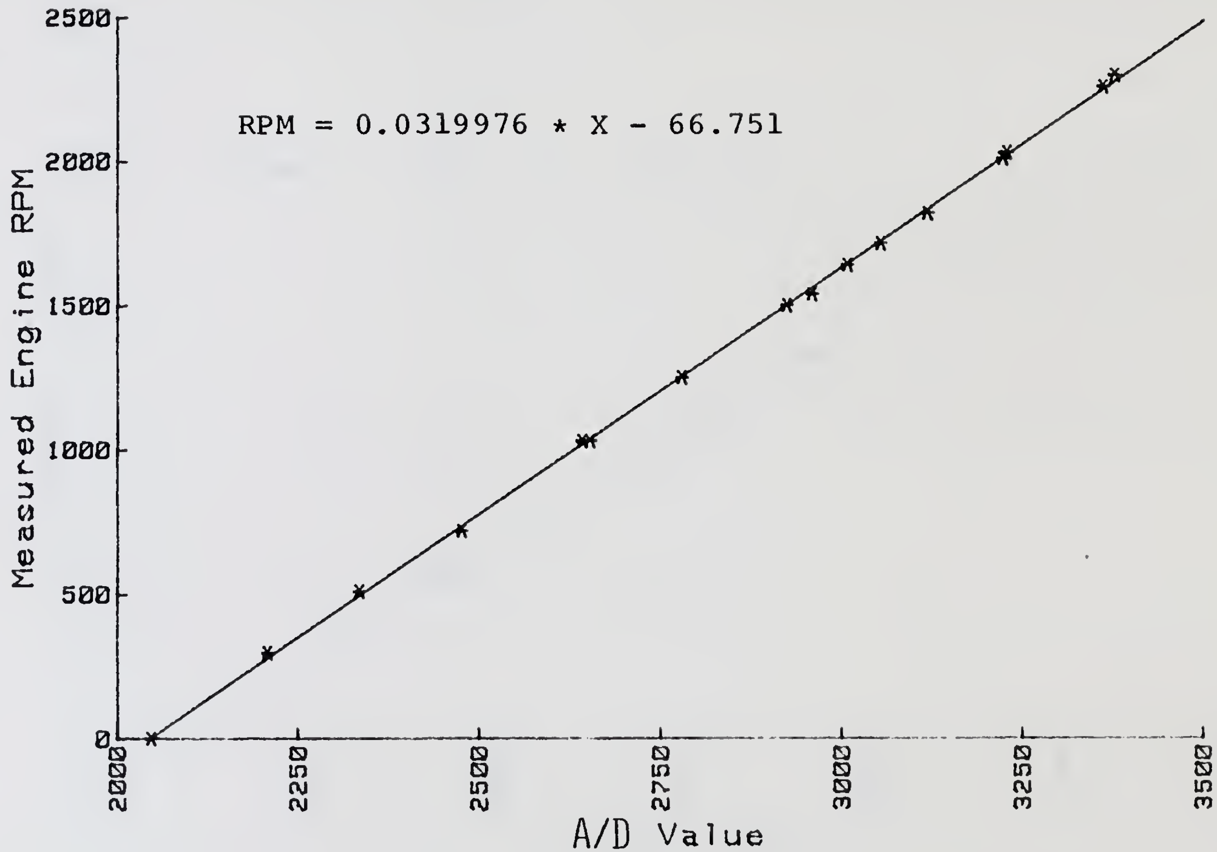


Figure C.6. Engine Speed Calibration Curve and Calibration Curve

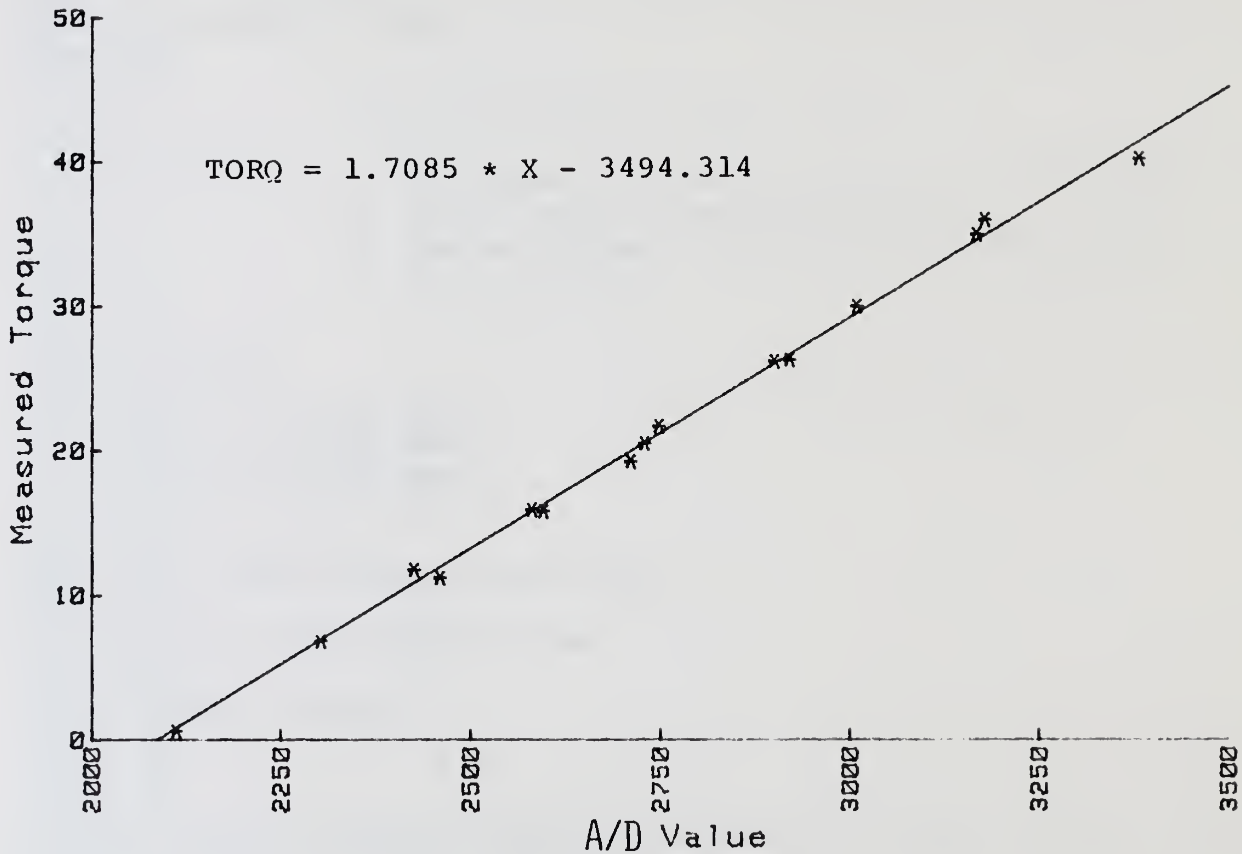


Figure C.7. Engine Torque Calibration Curve and Data Points

APPENDIX D

DATA ACQUISITION PROGRAM LISTING

```
C         **** DIESEL ENGINE DATA ACQUISITION AND CONTROL PROGRAM ****
C                   BRYAN OAKES
C                   SEPT. 1983
          PROGRAM DIESEL
          IRUN=0
          REAL PATM,SPGR,FST,ND
          RPM=100.
10        TYPE 6
          TYPE *,'         Current command options are;'
          type *,' '
          type *,'         1. Data acquisition and display subroutine.'
          type *,'         2. Input data through keyboard.'
          type *,'         3. Engine RPM and load setting subroutine.'
          TYPE *,'         4. Exit program.'
          type 11
          TYPE 30
          ACCEPT 51,IM
          IF(IM.EQ.'1') GOTO 200
          IF(IM.EQ.'2') GOTO 300
          IF(IM.EQ.'3') GOTO 400
          IF(IM.EQ.'4') GOTO 500
          GOTO 10
200       CALL RUN (PATM,SPGR,FST,DN,IRUN)
          GOTO 10
300       CALL DATIN (PATM,SPGR,FST,DN)
          GOTO 10
400       CALL ENGSET (RPMSET)
          GOTO 10
500       TYPE 37
          GOTO 999
6         FORMAT (///,X,'DIESEL ENGINE DATA AQUISITION AND CONTROL PROGRAM',//)
11        format (/////,'  Enter desired option.',)
30        FORMAT(X,'>',$)
37        FORMAT(X,'RETURNING TO RT-11:SJ')
51        FORMAT(1A1)
999       CONTINUE
```

```
          STOP
          END
C
C         **** CONSTANT DATA INPUT ****
C
          SUBROUTINE DATIN (PATM,SPGR,FST,DN)
301       TYPE 302
302       FORMAT(/////,X,'CONSTANT PARAMETERS',/)
305       type *,'Options 1 through 5 allow entering the parameters that remain'
          type *,'constant during data reduction. Typing 7 returns the user to'
          type *,'the calling subroutine.'
          type *,' '
          TYPE 370
          TYPE 371,PATM
          TYPE 372,SPGR
          TYPE 373,FST
          TYPE 374,DN
          type *,'     5. Return'
          type *,' '
          type *,'Enter desired option.'
306       TYPE 368
          ACCEPT 378,ID
          IF(ID.EQ.'1') goto 320
          IF(ID.EQ.'2') goto 325
          IF(ID.EQ.'3') goto 330
          IF(ID.EQ.'4') goto 335
          IF(ID.EQ.'5') goto 399
          GOTO 306
320       type *,' '
          type *,' Enter new value for atmospheric pressure.'
          accept 360,PATM
          goto 301
325       type *,' '
          type *,' Enter new value for specific gravity of fuel sample.'
          accept 360,SPGR
          goto 301
```

```
330     type *,' '
        type *,' Enter new value for fuel sample temperature.'
        accept 360,FST
        goto 301
335     type *,' '
        type *,' Enter diameter of air inlet nozzle.'
        accept 360,DN
        goto 301
360     format (1f8.4)
368     FORMAT(X,'>',$)
370     FORMAT(/)
371     FORMAT(5X,'1. ATMOSPHERIC PRESSURE          ',F6.2,' in. Hg')
372     FORMAT(5X,'2. FUEL SAMPLE SPECIFIC GRAVITY ',F6.4)
373     FORMAT(5X,'3. FUEL SAMPLE TEMPERATURE       ',F6.3,' deg. F')
374     FORMAT(5X,'4. NOZZLE DIAMETER               ',F6.3,' in.')
378     FORMAT(A1)
399     RETURN
        END
C
C       **** ENG RPM & TORQUE SET ****
C
        SUBROUTINE ENGSET
        REAL RPMSET,TORSET,VAL
401     type 402
402     format (/////,x,'ENGINE SPEED AND LOAD SET',/)
404     TYPE 470,IRPM,IT
        type *,'          Current command options are;'
        type *,' '
        type *,'          1. to change engine RPM'
        type *,'          2. to change engine load'
        type *,'          3. to return'
        type *,'          4. to display RPM and load'
405     TYPE 477
        ACCEPT 474,IE
        IF(IE.EQ.'1') GOTO 410
        IF(IE.EQ.'2') GOTO 415
```

```
      IF (IE.EQ.'3') GOTO 499
      IF(IE.EQ.'4') CALL SPEED
      GOTO 405
406   TYPE *,'* Input value out of range.'
      GOTO 405
410   type *,' Input an integer value for desired RPM.'
      accept 475,IRPM
      IF(IRPM.GT.2500) GOTO 411
      GOTO 420
411   TYPE *,'Input value out of range.'
      goto 410
415   type *,' Input an integer value for desired torque. (0 TO 60)'
      ACCEPT 475,IT
      IF (IT.GT.60) GOTO 416
      GOTO 420
416   TYPE *,'input value out of range.'
      goto 415
C     ---convert requested rpm and torque to value between 0 and 255---
420   IR=INT(.0755*FLOAT(IRPM))
      L=INT(1.85*FLOAT(IT))*256
      IOUT=IR+L
      CALL IPOKE("167772,IOUT)
      GOTO 401
470   FORMAT(X,'Current values;   RPM = ',I4,'   TORQUE = ',I2,'ft.lbs.',/)
474   FORMAT(A1)
475   FORMAT(I4)
477   FORMAT(//,x,'Enter desired option.',/,X,'>',$)
499   RETURN
      END
C
C     **** SUBROUTINE RUN ****
C
      SUBROUTINE RUN (PATM,SPGR,FST,DN,IRUN)
      INTEGER OCT
      REAL IHP,MECH,MEP,MAIR,MWTR,MFUEL,LHV,TOT,D,MF
      CD=.98
```

```
      PI=3.1415927
      DIMENSION CH(13,100),AVE(13),SD(13)
110   TYPE 111
      type *,'           Current command options are;'
      type *,' '
      type *,'           1. Begin data acquisition and display results.'
      type *,'           2. Print copy of displayed data on the line
     *printer.'
      type *,'           3. Display the results of the last run.'
      TYPE *,'           4. Change RPM or Torque'
      TYPE *,'           5. Display mean and std. deviation'
      type *,'           6. Return '
      TYPE *,'           7. Display RPM and Torque'
181   TYPE 198
      ACCEPT 182,IR
      IF(IR.EQ.'1')GOTO 115
      IF(IR.EQ.'2')GOTO 185
      IF (IR.EQ.'3') GOTO 166
      IF (IR.EQ.'4') GOTO 183
      IF (IR.EQ.'5') GOTO 300
      IF(IR.EQ.'6')GOTO 399
      IF(IR.EQ.'7')CALL SPEED
      GOTO 110
115   DO 130 I1=1,100
      OCT="1
      DO 120 I2=1,13
      CALL IPOKE("170400,OCT)
      CH(I2,I1)=IPEEK("170402)
120   OCT=OCT+"400
130   CONTINUE
C     --- compute mean and SD for each channel ---
      DO 140 I3=1,13
      TOT=0.0
      DO 135 I4=1,100
135   TOT=TOT+FLOAT(CH(I3,I4))
      AVE(I3)=(TOT)/100.
```

```
      D=0.0
      DO 138 I5=1,100
138   D=D+(AVE(I3)-CH(I3,I5))**2
      V=ABS(D/100.)
      SD(I3)=SQRT(V)
140   CONTINUE
141   CONTINUE
C     -- convert data into std. units using calibration curves --
      TAIR=AVE(1)*2.508-5126.3
      TEXH=AVE(2)*2.508-5126.3
      TWIN=AVE(3)*2.508-5126.3
      TWOUT=AVE(4)*2.508-5126.3
      TFUEL=AVE(5)*2.508-5126.3
      TIN=TAIR
      PA=PATM*.48977
      PAIR=PA-(AVE(7)*(3.756E-3)-7.512)*0.036129
      PIN=PA+(AVE(8)*(1.5445E-2)-31.291)*.48977
      PEXH=PA+(AVE(9)*(5.3712E-3)-10.480)*0.036129
      MF=AVE(10)*(4.0629E-6)-7.80E-3
      MWTR=AVE(11)
      TORQ=AVE(12)*.032-66.75
      RPM=AVE(13)*1.71-3494.3
C     -- compute calculated parameters --
143   IF (SPGR) 144,144,145
144   TYPE *,'Specific gravity of fuel out of range.'
      CALL DATIN (PATM,SPGR,FST,DN)
      GOTO 143
145   IF(PATM) 146,146,147
146   TYPE *,'Atmospheric pressure out of range.'
      CALL DATIN (PATM,SPGR,FST,DN)
      GOTO 141
147   AREA=3.14159*(DN**2)/4.
      IF(AREA) 148,148,149
148   TYPE *,'Nozzle diameter not in range.'
      CALL DATIN (PATM,SPGR,FST,DN)
      GOTO 143
```

```
149     SG60=SPGR+((FST-60.)/3600.)
        SGFUEL=SG60-((TFUEL-60.)/3600)
        MFUEL=SGFUEL*MF
        API=141.5/SG60-131.5
        LHV=16380.+(60.*API)
        BHP=2.0*PI*TORQ*RPM/33000.
        FTORQ=10.636+1.219E-2*RPM
        FHP=(1.904E-4)*FTORQ*RPM
        IHP=BHP+FHP
        MECH=BHP/IHP
        MEP=1.4208*TORQ
        SFC=3600.*MFUEL/BHP
        IF (MFUEL.LT.0.00001) MFUEL=0.00001
        THERM=0.70694*BHP/(MFUEL*LHV)
        Y=(PA-PAIR)/PA
        X=Y-1.0714*(Y**2)
        IF (X) 150,151,151
150     X=-X
151     MAIR=8.02*CD*PA*AREA*SQRT((X)/(53.34*(459.7+TAIR)))
        AF=MAIR/MFUEL
        SCAV=MAIR*685.0438*(TIN+459.7)/PEXH/RPM
        P1=(PA-PAIR)/.036129
        P2=(PIN-PA)/.48977
        P3=(PEXH-PA)/.036129
C       -- output measured and computed engine parameters --
166     TYPE 165,IRUN
        TYPE 152,RPM,TORQ
        TYPE 153
        TYPE 154,TIN,BHP
        TYPE 155,TEXH,FHP
        TYPE 156,TWIN,IHP
        TYPE 157,TWOUT
        TYPE 158,TFUEL,MECH
        TYPE 188,PATM,THERM
        TYPE 189,P1,MEP
        TYPE 190,P2,SFC
```

```
      TYPE 191,P3,SCAV
      TYPE 163,MFUEL,MAIR
      TYPE 164,MWTR,AF
      TYPE *,' '
      TYPE *,' '
      TYPE *,'Commands: <1>read data <2>print <3>display <4>set RPM & Torque
     *'
      TYPE *,'<5>display mean & SD <6>return <7> display RPM & Torque'
      goto 181
183   CALL ENGSET
      GOTO 110
185   IRUN=IRUN+1
      WRITE (6,165)IRUN
      WRITE (6,152)RPM,TORQ
      WRITE (6,153)
      WRITE (6,154)TAIR,BHP
      WRITE (6,155)TEXH,FHP
      WRITE (6,156)TWIN,IHP
      WRITE (6,157)TWOUT
      WRITE (6,158)TFUEL,MECH
      WRITE (6,188)PATM,THERM
      WRITE (6,189)P1,MEP
      WRITE (6,190)P2,SFC
      WRITE (6,191)P3,SCAV
      WRITE (6,163)MFUEL,MAIR
      WRITE (6,164)MWTR,AF
      CLOSE (UNIT=6)
      GOTO 181
300   type *,' '
      type *,' '
      type *,'                         MEAN                    STD DEVIATION'
      TYPE *,'AIR TEMP          ',AVE(1),SD(1)
      TYPE *,'EXHAUST TEMP      ',AVE(2),SD(2)
      TYPE *,'WATER IN          ',AVE(3),SD(3)
      TYPE *,'WATER OUT         ',AVE(4),SD(4)
      TYPE *,'FUEL TEMP         ',AVE(5),SD(5)
```

```
      TYPE *,'AIR PRESSURE    ',AVE(7),SD(7)
      TYPE *,'BOOST AIR PRESS',AVE(8),SD(8)
      TYPE *,'EXHAUST PRESS   ',AVE(9),SD(9)
      TYPE *,'FUEL MASS FLOW ',AVE(10),SD(10)
      TYPE *,'WTR MASS FLOW  ',AVE(11),SD(11)
      TYPE *,'TORQUE          ',AVE(12),SD(12)
      TYPE *,'RPM             ',AVE(13),SD(13)
      GOTO 181
111   FORMAT(/////,X,'DATA AQUISITION AND REDUCTION',/)
142   FORMAT(2F10.2)
182   FORMAT(1A1)
165   FORMAT(X,'RUN NO. ',I2)
152   FORMAT(X,'RPM = ',F6.1,5X,'TORQUE = ',F5.2)
153   FORMAT(/,10X,'Measured Parameters',20X,'Computed Parameters',/)
154   FORMAT(2X,'Atmospheric temp.',6X,F8.1,' deg F',5X,'Brake Horsepower',
     *11X,F4.1,' HP')
155   FORMAT(2X,'Exhaust Temp.',10X,F8.1,' deg F',5X,'Friction HP',16X,F4.1
     *,' HP')
156   FORMAT(2X,'Coolant inlet temp',5X,F8.1,' deg F',5X,'Indicated HP',15X,
     *F4.1,' HP')
157   FORMAT(2X,'Coolant outlet temp',4X,F8.1,' deg F')
158   FORMAT(2X,'Fuel temp',14X,F8.1,' deg F',5X,'Mechanical efficiency',6X,
     1F6.4)
188   FORMAT(2X,'Atmospheric press.',5X,F8.3,' in Hg',5X,'Thermal efficiency
     1',9X,F6.4)
189   FORMAT(2X,'Inlet air pressure',4X,F8.3,' in H2O',5X,'Mean effective pr
     *ess.',3X,F5.2,' psia')
190   FORMAT(2X,'Boost air press.  ',5X,F8.2,' in Hg',5X,'SFC (lbm/hp-hr)',
     *13X,F5.3)
191   FORMAT(2X,'Exhaust gas press.'4X,F8.2,' in H2O',5X,'Scavenge ratio',12
     1X,F5.2)
163   FORMAT(2X,'Fuel mass flow rate',4X,F8.5,' lbm/s',5X,'Air mass flow rat
     *e',2X,F6.2,' lbm/s')
164   FORMAT(2X,'Coolant mass flow',6X,F8.2,' lbm/s',5X,'Air/Fuel ratio',12X
     *,F7.3)
198   FORMAT(/,x,'Enter desired option',/,X,'>',$)
```

```
399     RETURN
        END
C
C
        SUBROUTINE SPEED
C
        REAL T,S,T1,S1
        INTEGER I1,I2
        T=0.0
        S=0.0
        DO 150 I=1,100
        CALL IPOKE ("170400,"5401)
        I2=IPEEK("170402)
        T=T+FLOAT(I2)
        CALL IPOKE ("170400,"6001)
        I1=IPEEK("170402)
        S=S+FLOAT(I1)
150     CONTINUE
        T1=(T/100.)*.032-66.75
        S1=(S/100.)*1.71-3494.3
        TYPE *,' '
        TYPE *,'RPM = ',S1,'   TORQUE = ',T1
        END
```

APPENDIX E

DATA REDUCTION CALCULATIONS

1. Fuel Mass Flow Rate (MFUEL);

   - fuel mass flow rate read directly from mass flow meter.

   MFUEL = MF (channel 9 of A/D converter)

2. Brake Horsepower (BHP); net rate of work

   BHP = (2 * PI * RPM * TORQ)/33000

3. Friction Horsepower (FHP);

   - compute friction torque (FTORQ) using curve fit equation developed from experimental data.

   FTORQ = 10.636 + (RPM * 1.219E-02)

   - compute friction horsepower (FHP)

   FHP = (2 * PI * RPM * FTORQ)/33000

4. Indicated horsepower (IHP); total engine work rate

   IHP = BHP + FHP

5. Mechanical Efficiency of Engine (MECH); net work rate divided by total work rate

   MECH = BHP/IHP

6. Mean Effective Pressure (MEP);

   MEP = 24 * PI * T / VD

   VD = displacement volume = 53.0685 in

7. Specific Fule Consumption (SFC); rate of fule usage divided by net work rate

   SFC = (3600 * MFUEL)/BHP

8. Thermal Efficiency of Engine (THERM);

- convert fuel sample specific gravity (SPGR) to specific gravity at 60 deg F (SG60)

SG60 = SPGR + (FST-60)/3600

- compute lower heating value of fuel (LHV)

LHV = 16380 + (API)

API = 141.5/SG60 -131.5

- compute thermal efficiency

THERM = (0.70694 * BHP)/(MFUEL * LHV)

9. Air Mass Flow Rate (MAIR) through air inlet nozzle

Y = (PA - PAIR)/PA

PA = atmospheric pressure (stagnation pressure)

PA - PAIR = pressure differential across nozzle

X = Y - (1.0714 * (Y ** 2))

1.5/(ratio of specific heats) = 1.0704

- compute air mass flow rate, this equation is accurate as long as Y<0.1

MAIR = 8.02*CD*PA*AREA*SQRT(X/(53.34*(459.7 + TAIR)))

AREA = area of air inlet nozzle

TAIR = stagnation temperature of air

53.34 = R = gas constant

10. Air-to-Fuel Ratio (AF); air mass flow rate divided by fuel mass flow rate

AF = MAIR/MFUEL

11. Scavenge Ratio (SCAV);

SCAV = (MAIR * 685 * (TIN + 459))/(PEXH * RPM)

PEXH = exhaust gas pressure

TIN = inlet air temperature

685 = (R/VD) * 720

VD = displacement volume = 53.0685 in^3

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